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Super-resolution Microscopy and Photo-lithography: How can one inspire the other

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Abstract. The principles of microscopy and lithography projection techniques are similar. To improve the resolution of the microscope or further reduce the image projection, both techniques face similar limitations, diffraction limits. The diffraction limit is a limitation of physical optics. In the development process of microscopes, to improve optical microscopy technology, researchers have proposed the idea of reducing the wavelength of light sources and increasing the numerical aperture based on the principle of diffraction limit generation. Modern scientists have proposed techniques to break through the diffraction limit and gradually increase the resolution of microscopes to further improve resolution. These breakthroughs also provide ideas for lithography technology, and researchers have invented techniques such as immersion lithography, multi-exposure, and two-photon direct writing. This article introduces the development process of super-resolution microscopy and lithography technology and analyzes the inspiration and influence of microscopy technology on lithography technology, that is, providing ideas for improving the accuracy of lithography technology.

Keywords: Super-resolution microscopy, photo-lithography, image projection

1. Introduction

The lithography machine is a device that uses optical projection principles to transfer specific patterns on a mask onto a substrate. It is widely used to transfer fine patterns such as chip circuits onto silicon wafers. The lithography machine plays a decisive role in the production and manufacturing of semiconductor products. The fineness of the patterns that can be projected by the lithography machine represents the level of semiconductor production technology. The microscope is a high-magnification magnifying glass based on optical principles or an electronic optical system. With the help of this device, it is possible to observe the structure of tiny objects and surface characteristics of materials that cannot be observed by the naked eye. When the resolution exceeds one-half of a wavelength, the diffraction limit is reached, which limits the imaging clarity of the microscope and the fineness of the projected patterns of the lithography machine.

Scientists have invented various technologies to improve the resolution of both technologies [1]. In the development process of the microscope, researchers invented the super microscope by using a light source with a smaller wavelength. They also improved the objective lens by using oil immersion and water immersion methods. The winners of the 2014 Nobel Prize in Chemistry were commended for inventing super-resolution fluorescence microscopy technology, which greatly increased the resolution of the microscope. Similarly, ASML's EUV system uses extreme ultraviolet light with a shorter wavelength to increase resolution, and Lin Benjian's immersion lithography technology is widely used in the production of lithography machines. In modern times, researchers have invented multiple exposure technology and two-photon direct writing technology by bypassing the diffraction limit, both of which improve the fineness of lithography technology [2].

This article introduces the development process and latest technologies of microscopes and lithography machines by studying the principles and resolution limitations of the two technologies. By analyzing the relationship between microscopy and optical technology, it is found that both technologies have similarities and are limited by the diffraction limit. However, research has shown that the latest technological developments and innovations in microscopy and lithography machines are similar in thinking. By connecting the commonalities between microscopy and lithography technology principles, it is found that the ideas and methods of innovation and technological breakthroughs in microscopy have a positive impact on lithography technology. The ideas in this paper, provide new ideas for the invention of a new generation of lithography machines, which is beneficial to the progress and innovation of the modern lithography machine industry.

2. The principle of the lithography system

The working principle of the lithography machine is based on optical projection technology. It utilizes the optical system to project the circuit design pattern onto a silicon wafer and then uses photosensitive materials to create the circuit pattern. The main components of the lithography machine include a light source, an optical projection system, a control system, as well as photoresist coating and developing systems.

It adopts a camera-like principle, reducing the fine patterns of integrated circuits on the photomask through the objective lens system in proportion and imaging them onto the silicon wafer. Then, chemical development is used, followed by ion beam etching, to obtain the fine patterns of integrated circuits etched onto the silicon wafer.

The optical system, consisting of an exposure light source, lenses, mirrors, and the like, is used to project the patterns on the photomask onto the silicon wafer. Its primary function is to generate a projection lens using a light source through the photomask to project the target pattern onto the substrate silicon wafer.

In practical optical imaging or projection systems, the influence of the diffraction limit must be taken into account. The diffraction limit refers to the fact that when an ideal object point is imaged through an optical system, due to diffraction, it is impossible to obtain an ideal image point, but instead, an Airy disk is formed. As a result, the image of each object point appears as a diffuse spot, and when two diffuse spots are close together, they become difficult to distinguish, thus limiting the resolution of the system. The larger the spot, the lower the resolution. The patterns on the photomask are a collection of actual object points, and when the desired image is fine, the object points on the photomask will be very close to each other. The corresponding diffuse spots will also be very close, affecting the transfer of the pattern. This limitation is a physical optical constraint caused by the diffraction of light.

3. Traditional methods for improving resolution

Researchers have quantified the impact of the diffraction limit. In 1873, the German physicist Ernst Abbe discovered the formula for the resolution limit of microscopes, known as the Abbe limit. It is approximately equal to half the wavelength of the light wave. The wavelength of violet light, the shortest in visible light, is approximately 400 nanometers, making the Abbe limit around 200 nanometers. This means that if the distance between two points reaches 200 nanometers, they cannot be distinguished using an optical microscope.

Abbe criterion:

$$\delta = \frac{0.61\lambda}{\mathrm{nSin}\alpha} \tag{1}$$

(δ: resolution ratio λ: wavelength n: refractive index α: aperture angle)

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To obtain clearer images with traditional optical microscopes, one approach involves using wavelengths shorter than visible light, such as ultraviolet (UV) light. August Kshler of Carl Zeiss introduced the UV microscope, which utilizes UV light with wavelengths below 380-360 nanometers to form images. Quartz or fluorite are often used to manufacture the lenses and objectives of these microscopes as they can transmit UV light with wavelengths as low as 200nm or even 185nm. When UV light with a shorter wavelength is reflected or transmitted by an object, it forms an image within the microscope. Due to its shorter wavelength, UV microscopes typically exhibit higher resolution than those using visible light. They can be employed to observe and study the structures and characteristics of microscopic organisms such as cells, viruses, and bacteria.

Another approach to enhancing the clarity of optical microscope images involves the use of oil-immersion or water-immersion objectives. As early as 1678, Robert Hooke proposed the idea of immersion microscopy. In 1877, Ernst Abbe discovered a superior medium—Canada balsam oil (n=1.515), which was then used to create the homogeneous oil-immersion objectives that are still widely used today [3]. Immersion microscopy, also known as oil-immersion microscopy, employs a high-refractive-index oil (such as Canada balsam oil) as the medium between the objective lens and the observed sample. This increases the numerical aperture of the microscope, thereby enhancing its resolution. When using high-magnification objectives (such as 100x), the low refractive index of air can cause refraction as light passes through the interface between air and the lens, degrading image quality. However, immersion microscopy reduces this refraction by introducing a high-refractive index oil between the objective and the sample. This allows light to focus better on the sample, improving image clarity and resolution. Consequently, immersion microscopy enables the observation of finer structures and details.

4. Inspiration which are from traditional optical microscopes

The renowned ASML (Advanced Semiconductor Material Lithography), a semiconductor equipment manufacturing company, manufactures EUV lithography machines, which employ extreme ultraviolet (EUV) light. The full name of the EUV lithography machine is Extreme Ultraviolet Lithography Machine. This is a lithography technique that uses EUV light with a wavelength ranging from 10 to 14 nanometers as its light source. The EUV light is generated by evaporating metallic materials such as lithium using a laser beam. The metal vapor is then heated through a high-temperature plasma process and focused through a tracking system within the lens. This technology enables precise patterning on silicon wafers, a crucial step in the manufacturing of advanced semiconductors and microprocessors. The use of EUV lithography in the semiconductor industry has significantly improved production efficiency and reduced costs, propelling the continuous evolution of electronic devices towards higher performance and smaller sizes.

Currently, the international monopoly of EUV lithography technology has taken shape, with ASML being the only company globally capable of providing EUV lithography equipment with a wavelength of 13.5 nanometers. This equipment serves as the core machinery for the production of large-scale integrated circuits, exerting a decisive influence on chip manufacturing processes. Specifically, chip wafers with dimensions smaller than 5 nanometers can only be produced using EUV lithography machines. The precision and efficiency of EUV lithography enable it to meet the increasingly demanding requirements of the semiconductor industry, particularly in the realm of advanced chip manufacturing. Given its uniqueness and technological superiority, the global demand for ASML's EUV lithography equipment remains high, further consolidating its position as the industry leader.

The invention of immersion lithography technology using oil-immersion objectives dates back to the late 20th century when Chinese scientist Dr. Lin Benjian began his research at International Business Machines Corporation (IBM). In 2002, Dr. Lin proposed the idea of using water as the immersion liquid to enhance the lithography resolution and successfully developed immersion microscopy technology in the following year.

The working principle of immersion lithography lies in utilizing a liquid with a high refractive index to increase the refractive index of the medium through which light passes between the

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lithography machine's lens and the silicon wafer. Typically, water or other special liquids are used to enlarge the numerical aperture of the lens, thereby reducing the diffraction effect of light. When light rays enter the high-refractive-index liquid from the air, refraction occurs, causing the focal point of the light on the silicon wafer to become smaller. This allows for the creation of finer patterns.

The introduction of immersion lithography has significantly improved the resolution and precision of photolithography processes, enabling the production of semiconductors with increasingly smaller features and higher densities. Dr. Lin's groundbreaking work in this field has had a profound impact on the semiconductor industry, contributing to the advancement of technology and the miniaturization of electronic devices.

The invention of wet lithography technology was an important breakthrough in semiconductor manufacturing technology, breaking the monopoly of dry lithography technology at that time and pushing lithography resolution to new heights. Compared to traditional dry lithography technology, immersion lithography technology has higher resolution, lower manufacturing costs, and a wider range of applications, bringing tremendous impetus to the development of the semiconductor industry.

5. Modern methods for improving resolution

As the Abbe limit states, the resolution of an optical microscope is limited by the wavelength of light. Therefore, theoretically, the maximum resolution that an optical microscope can achieve under visible light (wavelength 400-780mm) is only 0.1wm, and the maximum magnification is only 2000 times.

It is worth noting that Abbe's concept of optical diffraction limit is based on the inherent wave nature of light waves, and many advanced optical microscopy techniques in contemporary times often rely on various peculiar effects generated by the interaction between light and matter to achieve this, which opens a gap for breaking through the optical diffraction limit.

The 2014 Nobel Prize in Chemistry was awarded to researchers in super-resolution microscopy, which includes two categories of far-field super-resolution technologies.

One type is to reduce the size of the Airy spot by shaping the excitation light and combining it with the nonlinear response of the material to light to reduce the spot. For example, Stimulated Emission Department microscopy, abbreviated as STED microscope, is a super-resolution fluorescence microscopy technique. Its principle is based on the Stimulated Emission Department process [4].

In an STED microscope, a high-intensity infrared light (STED light) is focused on the sample, overlapping with another visible light (excitation light) used to excite fluorescence. When STED light is irradiated on the sample, it triggers the stimulated radiation process of the fluorophore, that is, the fluorophore will emit a photon of the same wavelength as the excitation light after absorbing STED light, and return to a low energy state [5]. This process will consume the excited state of the fluorescent group, thereby reducing or eliminating the spontaneous fluorescence of the fluorescent group, achieving fluorescence loss or erasure. This can reduce the size of Airy spots. By precisely controlling the intensity and shape of STED light, the loss area of fluorescence can be precisely controlled at the micrometer scale, thereby achieving super-resolution reconstruction of fluorescence images [4].

The high resolution and image contrast of STED microscopes makes them an indispensable tool for biomedicine, materials science, and other fields, allowing researchers to observe smaller and finer biological structures and molecular interactions.

Another method is to bypass the diffraction limit, by choosing only one of the two similar points, then only one airy spot will appear, and there will be no overlap of Airy spots, thus bypassing the diffraction limit.

When we irradiate and observe the first point, the second point does not emit light and naturally does not produce Airy spots that affect our observation of the first point. The center point of the former Airy spot is the exact location of the fluorescent molecule. Next, by some means, the second point is illuminated. At this time, the first point is no longer within the illumination range of the spot, and it will not interfere with the observation of the second point. Through this "time-for-space" design,

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it skillfully circumvents the constraints of the Abbe limit (microscope resolution limit), greatly improving the resolution of optical microscopes.

Stochastic Optical Reconstruction Microscopy(STORM) applied this method, which is based on the principles of single-molecule fluorescence imaging and statistics. It uses organic fluorescent molecules to dye, and these fluorescent molecules can be excited by laser irradiation and emit fluorescence. Unlike traditional fluorescence microscopy, STORM uses a series of clever operations to make each fluorescent molecule emit only a very small number of photons after excitation and quickly return to a non-fluorescent state. In this process, the fluorescence emission of the fluorescent molecules is random, so it is called “random optical reconstruction” [4]. Next, by collecting these extremely small amounts of fluorescence signals with a high-speed camera and processing the images with computer algorithms, it is possible to reconstruct the super-resolution image of the sample. This process is based on the principle of statistics, by collecting a large number of random fluorescence signals and using algorithms to process and analyze these signals, we can obtain high-resolution images of the sample [6].

The impact of STORM technology is profound. It breaks the resolution limit of traditional optical microscopes, enabling people to observe smaller and more subtle biological structures and molecular interactions. This enables biomedical research to gain a deeper understanding of the microscopic world of life, thereby promoting scientific research and application development in related fields.

6. Similar methods which are from the field of lithography

The first method is to reduce the size of the Airy disk. For example, the stimulated emission depletion (STED) lithography technique is similar to the principle of STED microscopy. It uses a normal excitation beam and an STED beam, and both lasers simultaneously act on the fluorescent sample [6]. By precisely controlling the shape and intensity of the STED beam, the loss area of the fluorophore can be precisely controlled on the nanoscale, achieving high-precision patterning of the sample surface.

STED lithography technology has the characteristics of high resolution, high accuracy, and high sensitivity. It has broad application prospects in nanomanufacturing, biomedicine, and other fields, but it still faces some challenges and limitations. For example, STED lithography technology requires high-intensity STED beams and precise control systems, making it expensive and technically difficult to implement.

Another method is to bypass the diffraction limit by spreading the adjacent objects of the fine pattern over two simple patterns, thus avoiding the overlap of Airy disks. For example, the Double-Patterning lithography technology is used to solve the problem of complex patterns that cannot be directly manufactured due to limitations in lithographic resolution. The main idea of this technology is to decompose a complex pattern into two or more simple patterns, then separately perform lithography and etching, and finally combine them to form the final complex pattern [5]. Two masks are typically used to print different parts of the pattern in double-patterning lithography. These two masks are used alternately during the lithographic process, with each mask containing only part of the final pattern. In this way, patterns with higher resolution and more complex structures can be manufactured[7].

It can effectively solve the problem of complex patterns that cannot be directly manufactured due to the limitations of lithographic resolution, thereby improving the performance and reliability of semiconductor devices. However, repeated lithographic operations are required, which increases the cost and time of large-scale production.

7. Conclusion

This paper studies the history of the development of microscopic technology and lithography technology, including traditional techniques and the latest modern technologies, such as ultraviolet microscopy, fluorescence microscopy, multiple exposures, and two-photon direct writing technology. By analyzing the principles of each technology, it studies the similarities between microscopic technology and lithography technology and discovers the connection between the two technologies.

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However, this article does not analyze the principles of each microscopic and lithographic technology but only analyzes the more mature technologies. The conclusion is not comprehensive. In future research, it is important to focus on studying the principles of the most advanced microscopic or lithographic technology and to find inspiration and ideas for the development of another technology. This discovery brings new ideas for the research of the latest microscopic and lithographic technologies in the future and has a guiding role in the innovation of a new generation of lithography machines.

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