Proceedings of the 5th International Conference on Materials Chemistry and Environmental Engineering
DOI: 10.54254/2755-2721/126/2025.20005

Application of Photolithography in Integrated Circuits

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Abstract: Integrated circuit (IC) manufacturing relies heavily on lithography, which drives device size reduction and performance improvement through precise pattern transfer. As the performance requirements of electronic devices continue to increase, lithography faces major challenges in terms of precision and efficiency. Currently, deep ultraviolet (DUV) and extreme ultraviolet (EUV) lithography technologies are mainstream, while technologies such as electron beam lithography (EBL) and directed self-assembly (DSA) are applied in specific high-precision fields. This paper reviews the current development status of lithography technology and analyzes its application in CMOS technology, 3D NAND flash memory, and high-performance computing components. The study also explores the main challenges facing photolithography, including technical bottlenecks, rising costs, and environmental impacts. In order to address these issues, the study emphasizes the importance of technological innovation and material improvement, especially in the development of new photoresists and mask materials and the promotion of environmentally friendly lithography technology. Therefore, it can be found that continued advances in lithography are essential to meet the changing needs of the semiconductor industry.

Keywords: Integrated Circuits, Photolithography, DUV Lithography, EUV Lithography.

1. Introduction

The rapid development of information technology has led to the ascendance of integrated circuits (ICs) as a pivotal driver of modern societal advancement. The manufacturing process of ICs is constantly evolving, among which lithography is the core link that determines the performance and cost of ICs. As the performance requirements of electronic devices continue to increase, the continuous reduction of device size has put forward higher requirements for the accuracy and efficiency of photolithography. This paper aims to analyze in-depth the current status of lithography application in integrated circuit manufacturing and to examine its role in the manufacturing of different types of integrated circuits. In addition, the technical challenges faced during the development of photolithography are studied and possible solutions are explored. The analysis of related literature and cases provides theoretical basis and technical support for the field of integrated circuit manufacturing, promotes the innovation of lithography technology, and meets the needs of the future development of the electronics industry. Through in-depth exploration of the basic principles and applications of lithography, the key role of photolithography in the manufacturing of integrated circuits is revealed, and corresponding solutions are proposed to provide theoretical support and technological innovation direction for the sustainable development of the integrated circuit industry.

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2. Overview of Photolithography

2.1. Fundamentals of Photolithography

Photolithography is crucial inmicro- and nanofabrication, which centers on the transfer of fine patterns onto semiconductor wafers or other substrate materials. This technology uses the interference, diffraction and absorption characteristics of light to achieve pattern transfer by controlling these physical phenomena. At the beginning of the process, the wafer surface is coated with a photosensitive resist, which undergoes chemical changes under light. And light is projected onto the resist layer through a mask, triggering a photochemical reaction and changing its solubility [1]. Following the development stage, the resist layer is removed from the unexposed or exposed area to form a pattern, then the unprotected wafer material is etched away, and finally the desired microstructure is formed on the wafer. Its accuracy directly affects the performance of integrated circuits, such as transistor size and chip function. As technology nodes evolve, feature sizes shrink from the micrometer to the nanometer scale, which requires higher resolution and pattern transfer accuracy [2]. To meet the requirements, photolithography continues to innovate, including the use of short-wavelength light sources, improved optical systems, and the development of new photoresists and advanced mask technologies. These innovations have facilitated technological advances that support miniaturization and performance enhancement of integrated circuits [3].

2.2. Main Types of Photolithography

2.2.1. Deep Ultraviolet (DUV) Photolithography

This type, the cornerstone in IC manufacturing, utilizes deep ultraviolet light at wavelengths from 193 nm to 248 nm to transfer microscopic patterns on silicon wafers. This technology has dominated the semiconductor industry since the 1990s, and its development marked the leap from micron to nanometer feature sizes for integrated circuits [2]. At its core, high precision pattern transfer is achieved by precisely controlling the interaction between the light source, mask and resist. As the demand for higher densities and smaller sizes in integrated circuit manufacturing continues to grow, DUV technology continues to undergo technological innovation. Among them, Phase Shift Mask technology improves the contrast and sharpness of patterns by changing the phase relationship between the light transmissive and opaque regions on the mask. Moreover, Optical Proximity Effect Correction utilizes advanced computational models to predict and correct distortions that may occur during the lithography process, thereby improving the accuracy and repeatability of the pattern. The introduction and development of these technologies have enabled DUV lithography to maintain its competitiveness in micron and even nanometer-scale manufacturing. In particular, it has successfully supported the need for high-density integration through the application of multiple exposures and multiple patterning techniques in the fabrication of integrated circuits at the 90 nm to 14 nm technology node. Despite competition from extreme ultraviolet lithography technology, DUV technology remains an important option for large-scale IC manufacturing due to its mature process and relatively low cost [4].

2.2.2. Extreme Ultraviolet (EUV) and E-beam Photolithography

They are two important lithography technologies in the current field of IC manufacturing, each showing unique advantages and limitations in different application scenarios. As early as 1958, the first high-resolution two-dimensional graphical structures were produced using electron-induced carbon contamination to form etch masks [5]. Extreme ultraviolet photolithography uses extreme ultraviolet light with a wavelength of 13.5 nanometers to achieve smaller feature sizes. Compared

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with DUV lithography, EUV technology has promoted the development of integrated circuits to 10 nanometers and below [6]. This technology has significant advantages in improving chip performance and reducing power consumption, especially in the development of artificial intelligence, 5G communications and supercomputing. However, it faces challenges in light source stability, mask manufacturing and photoresist materials, which limit the speed and scope of its widespread application. Nevertheless, with the continuous advancement of technology, EUV technology has shown strong potential and market value [7]. Electron beam lithography technology utilizes a focused electron beam to form micromachined patterns on the surface of silicon wafers, which enables nanoscale pattern transfer and shows unique advantages in special application scenarios such as microelectromechanical systems (MEMS), nano-electronic device fabrication, and high-precision mask production. While the low exposure efficiency of EBL limits its application in mass production, its high resolution and precision in specific areas make it an indispensable technology. The development of both technologies requires not only innovation in the technology itself, but also support from materials science. In addition, advances in technologies such as lithography motion stage control, illumination system technology, projection objective lens aberration detection, ultra-precise motion stage control, and contamination control of immersion lithography systems provide guarantees for the high performance and stability of lithography technology [8][9].

2.2.3. Directed Self-Assembly (DSA) Technology

This type is an emerging photolithography technology, which controls the self-assembly process of molecules in a specific direction to form an ordered pattern through the interaction force between the molecules of the material [9]. DSA technology is regarded as a potential alternative technology for the future of IC fabrication due to its advantages of low cost, high efficiency and scalability. Currently, DSA technology is in a rapid development stage, and researchers are exploring different material systems and process conditions to improve the patterning accuracy and application range of DSA technology. The continuous development of lithography requires the dual drive of technological innovation and material improvement. Motion table control methods for photolithography, illumination system technology, and projection objective lens aberration detection technology are all key technologies in the development of lithography, and their research progress provides a guarantee for the high performance and stability of lithography technology. In the face of the ever-challenge of shrinking IC feature sizes, exploring and developing new lithography technologies, such as EUV, E-beam lithography, and DSA, are significant in promoting the development of IC technology. Innovations in lithography also require the cross-fertilization of multiple disciplines, such as materials science, optical engineering, and chemical engineering, to achieve higher precision, higher efficiency, and lower cost lithography processes.

3. Major Applications of Photolithography in Integrated Circuits

3.1. Applications in CMOS Technology

CMOS technology (complementary metal oxide semiconductor technology) is the mainstream technology for integrated circuit manufacturing. Its basic principle is to realize the functions of logic gates and storage units by manufacturing N-type and P-type MOSFETs (metal oxide semiconductor field effect transistors) on silicon wafers [10]. CMOS technology is known for its low power consumption, high integration and high reliability. In CMOS chip manufacturing, photolithography plays a critical role in ensuring high-density integration of the chip by accurately replicating circuit patterns [8]. First, in terms of advanced process nodes, lithography, especially extreme ultraviolet lithography (EUV), is widely used in the manufacture of transistors with smaller feature sizes in the CMOS process node at 7 nm and below, where it can achieve higher levels of integration, allowing

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chips to incorporate more functionality while reducing power consumption. For example, EUV technology is used in the manufacture of modern smartphones, data centers and high-performance computing chips, significantly improving transistor density and reducing power consumption. Secondly, in terms of improving chip performance, the precision of lithography technology directly affects the size and alignment precision of transistors, thus affecting chip performance. Through the use of advanced lithography, smaller transistors can be manufactured, switching speed can be increased, and delays can be reduced, thus improving the overall performance of the chip. For example, lithography technology can achieve higher operating frequencies and faster data transmission speeds when manufacturing processors to meet the needs of modern computing and communications. Third, in terms of reducing power consumption, with the development of photolithography, chips can be produced with smaller feature sizes, reducing the power consumption of the chip. Advanced lithography technologies such as EUV can achieve lower leakage current and higher energy efficiency. For example, the latest CMOS chips can maintain high performance when running in low-power mode, which is particularly important for mobile devices and high-performance computer systems. Finally, in terms of lithography optimization, process optimization techniques such as optical proximity correction and light source mask co-optimization are used in lithography to improve lithographic precision and reduce manufacturing defects. These techniques reduce pattern distortion and improve the quality of the final product.

3.2. Applications in 3D NAND Flash Manufacturing

Photolithography is used in many specific applications. First, in the manufacture of multi-layer structures, photolithography is used to accurately transfer circuit patterns on each layer of silicon wafers. Each layer of pattern must be accurately aligned with the lower layer to ensure that each vertically stacked memory cell can work properly. For example, when manufacturing 64-layer or 128-layer 3D NAND flash memory, photolithography technology needs to achieve extremely high alignment accuracy to ensure that the pattern of each layer can be accurately aligned with the target position. This poses a huge challenge to photolithography technology because with each additional layer, the manufacturing complexity and the requirements for photolithography accuracy will be significantly increased. Second, the production of vertical vias is another important application in the manufacture of 3D NAND flash memory [11]. Vertical vias are used to establish electrical connections between different storage layers. It is necessary to accurately locate the position of the holes at multiple levels and ensure that the size and shape of the holes meet the design requirements. Deviations in any manufacturing process may cause electrical connection problems, thereby affecting the overall performance of the chip. The main issues include the difficulty of precision control, the challenges of photoresist materials, and the problems of manufacturing costs and productivity. As the number of 3D NAND layers increases, lithography faces higher precision control requirements. During the pattern transfer process, each layer accumulates small alignment errors that can affect the quality of the final product. In addition, the challenge of photoresist materials is also an important issue. To accommodate the multilayer structure of 3D NAND, photoresist materials need to have excellent interlayer resolution and etch resistance. However, conventional photoresist materials may not be able to meet these requirements, so new photoresist materials need to be developed to meet the manufacturing needs of 3D NAND. Because of the complexity of the manufacturing process, manufacturing cost and productivity issues are also important challenges for lithography.

3.3. Applications in High Performance Computing

In the field of high performance computing, the use of lithography is critical. As computing needs continue to grow, the demands on processor performance, including central processing units, graphics

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processing units, and emerging artificial intelligence chips and application-specific integrated circuits, require lithography to achieve smaller feature sizes and higher levels of integration to meet the stringent requirements of high-performance computing [12]. Modern high-performance processors need to enable precise pattern transfers at the nanometer scale to support higher transistor densities and lower power consumption. Meanwhile, the requirements for high throughput and high yield are also increasing. The increase in the number of processor cores and the complexity of functional units require lithography technology to maintain high precision during the production process to ensure that the quality of chips produced on a large scale is stable and defect-free. Innovations in lithography technology have played a key role in meeting these needs. First, EUV technology was introduced to manufacture advanced process nodes of 7 nanometers and below. EUV technology uses an extreme ultraviolet light source of 13.5 nanometers, which can achieve higher resolution and smaller feature sizes than traditional deep ultraviolet lithography (DUV). This not only improves production efficiency, but also significantly improves chip performance. Secondly, photoresist materials have also made significant progress. To meet the needs of EUV technology, new EUV photoresist materials have been developed. These materials have higher resolution and better etching resistance, and can remain stable under extreme ultraviolet light irradiation to ensure the accuracy of pattern transfer. In addition, lithography process optimization technologies such as optical proximity correction and light source mask co-optimization have also been widely used. These technologies optimize the pattern transfer effect by adjusting the optical system and mask design in the lithography process, reduce defects in the manufacturing process, and improve chip performance and production yield.

4. Challenges in Photolithography

4.1. Technical Bottlenecks

As the feature size of integrated circuits continues to shrink, conventional lithography is approaching its physical limits. Optical diffraction limits further improvements in lithography resolution, which requires the development of new lithography techniques, such as EUV and EBL, to achieve smaller feature sizes [13]. The EUV technique uses a shorter wavelength and is capable of creating finer circuit patterns, but it also brings with it an increase in technological difficulty and cost. The chemicals and materials used in the lithography process have an impact on the environment. The development of environmentally friendly lithography, such as the use of biodegradable and low-polluting photoresist materials and water-based lithography processes, is becoming a hot research topic.

4.2. Solutions

Technological innovation is key to overcoming the challenges of lithography, including the development of new lithography principles, new lithography materials and improved lithography structures. High numerical aperture EUV lithography can be developed to improve exposure resolution. Technologies such as nanoimprint lithography and electron beam lithography are also being explored, which promise higher resolution and lower cost. The development of new lithography materials is critical to improving lithography performance. Researchers are developing higher resolution, more durable and flexible photoresist and mask materials. These new materials can improve the precision and reliability of the lithography process while reducing production costs and environmental impact. Through continuous technological innovation and material improvements, lithography is expected to overcome current challenges and continue to drive the development of IC technology. The development of environmentally friendly lithography will also help to realize the sustainable development of the industry.

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5. Conclusion

Photolithography plays a central role in integrated circuit manufacturing, and its progress is crucial to the evolution of the semiconductor industry. Despite resolution limitations, rising costs, and environmental challenges, photolithography is overcoming these challenges through continuous innovation and material improvements. The application of extreme ultraviolet lithography technology has improved manufacturing accuracy, enabling integrated circuits to achieve smaller feature sizes, while emerging technologies such as nanoimprint lithography and electron beam lithography are also advancing to improve resolution and production efficiency. Meanwhile, the development of new photoresists and environmentally friendly technologies will help reduce costs and environmental impact. In the future, the continued development of photolithography will rely on technological innovation and interdisciplinary collaboration to meet the growing demand for integrated circuits and support the continued progress of the semiconductor industry.

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