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# Application of Photolithography and Etching Processes in Digital Integrated Circuit Manufacturing

**Junyi Wen**

Changchun University of Science and Technology, Changchun, 130022, China
Corresponding author: 2023004979@mail.cust.edu.cn

**Abstract:**

As semiconductor technology nodes continue to shrink, the accuracy and coordination of lithography and etching—two key patterning processes in digital integrated circuit manufacturing—directly determine circuit performance and integration levels.This article aims to analyze the key technical points of these two processes. The article first elaborates on the methods of enhancing resolution in lithography technology by utilizing DUV/EUV light sources, as well as the matching relationship between these methods and the lithography resin materials. It also compares the principles and technical characteristics of wet etching and dry etching. This study systematically analyzed key technical aspects of lithography and etching processes to establish an experimental data-driven process parameter optimization model. Findings indicate that development process parameters significantly impact depth of focus, while etching uniformity can be improved by 40% through multi-parameter synergistic optimization. The research provides theoretical foundations and practical guidance for process co-optimization in advanced manufacturing.

**Keywords:** Lithography, Etching, Integrated Circuit Manufacturing, Process Optimization

## 1. Introduction

Due to the advancement of semiconductor technology, digital integrated circuits need to improve their manufacturing process while ensuring high performance, low power consumption and high integration. Therefore, how to enhance the two key technologies of lithography and etching to make chips smaller and achieve some previously unattainable functions has become a very important issue. These two technologies can largely determine the graphic accuracy and functional realization of devices. Therefore, if one wants to improve the manufacturing process of devices to produce more precise structures to enhance performance and achieve a higher yield rate by improving lithography or etching technology, the connection and interaction between the two should be emphasized.

In recent years, significant breakthroughs have been made in lithography and etching processes. For lithography, the main advancement lies in the use of

EUV light sources and the corresponding optimization of the optical system, which has achieved the goal of enhancing the resolution of pattern transfer. As for etching, more emphasis has been placed on the precise control of temperature and flow fields in wet etching, as well as the understanding of the plasma mechanism and the stable control of wafer temperature in dry etching. However, as the process node enters the nanometer and even sub-nanometer scale, issues such as the high power and cost of EUV light sources, random variations, and how to coordinate high aspect ratio etching profiles and three-dimensional structures remain challenging.

This article introduces the core technical points of photolithography and etching processes. It discusses the improvement paths of resolution in photolithography and the etching and photoresist, compares and analyzes the principles and applicable scenarios of wet and dry etching, and explores the influence factors of key parameters on depth of focus, uniformity, etc. based on experimental data. It also proposes optimization methods for the processes, providing a basis for the manufacturing of high-precision integrated circuits.

# 2. Foundation of Lithography Process

Lithography technology is the core process for transferring patterns in integrated circuit manufacturing. Its basic principle involves using an optical system to project the patterns on the mask onto the surface of a silicon wafer coated with photoresist. Through exposure and development, the desired patterns are formed. The precision of the lithography process directly affects the performance and integration level of the devices.

## 2.1 The Impact of Resolution

The traditional optical lithography technology is limited by the existence of optical diffraction, but by increasing the numerical aperture, shortening the wavelength of the light source, or reducing the process influence coefficient (such as off-axis illumination OAI, phase-shifting mask PSM, optical proximity effect correction, etc.) it is possible to improve the resolution to a certain extent [1].Currently, the mainstream lithography technologies employ deep ultraviolet (DUV) and extreme ultraviolet (EUV) light sources. DUV lithography typically uses ArF laser with a wavelength of 193 nm, while EUV lithography employs extreme ultraviolet light with a wavelength of 13.5 nm, which enables smaller feature sizes. Compared with previous lithography technologies, extreme ultraviolet lithography technology offers higher resolution, faster processing speed and lower operating costs [2].In conclusion, higher resolution requirements impose stricter demands on both the optical system and the mask plate.

## 2.2 Photomask Resin Material

Photoresist, also known as photo-sensitive resist, is the core photosensitive material in the photolithography process and directly affects the accuracy and yield of the chips. Photoresist is divided into two types: positive resist and negative resist. Positive resist is widely used in the photolithography process. When exposed to light, it becomes soluble and is washed away during the developing process, thereby enabling the production of high-resolution patterns with clear edges. Positive resist is a high-contrast photoresist and is easy to produce fine patterns. Negative resist, when exposed to light, the exposed area becomes insoluble and remains after developing, while the unexposed area is removed. Negative resist has good mechanical strength and heat resistance, and is very suitable for thick film applications and processes requiring high durability [3].

# 3. Etching Process Basics

Etching is an important step in the manufacturing process of semiconductor silicon chips. It selectively removes the desired parts or unwanted parts on the wafer through chemical means. Its main functions include transferring optical patterns onto the wafer surface for selective etching, trimming and refining the edge contours, and cleaning the surface. There are mainly two types of etching techniques: wet etching and dry etching [4].

## 3.1 Wet Etching

Wet etching is a technique that removes materials by immersing the substrate in a chemical etching solution. It relies on specific chemical reagents to selectively react with the unprotected areas on the wafer that are not covered by the photomask, converting them into soluble compounds and then washing them away. Wet etching mainly depends on chemical reactions, so the control of process parameters is very important. Therefore, choosing the appropriate chemical reagents, material ratios, and temperatures all require precise adjustments to achieve the most suitable etching rate and the best selection [5].

## 3.2 Dry Etching

Dry etching refers to a type of etching process where ions or free radicals generated by low-pressure discharge in the plasma react chemically with the material or cause the material to be ejected through physical impacts such as bombardment. When plasma reaches equilibrium during ionization and recombination processes, it becomes stable, resulting in discharge phenomena and generating light. In a gas environment, free electrons accumulate sufficient kinetic energy under the influence of an external electric

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field. When electrons collide with gas molecules at a specific speed, they cause the molecules to ionize and release secondary electrons; these secondary collisions occur continuously, eventually leading to an avalanche-like increase in the number of electrons and ions. The plasma formed after gas ionization contains electrons, ions, as well as free radicals in forms such as molecules, atoms, and atomic groups. These free radicals have strong chemical reactivity and can react with the surface of the material to be etched and form volatile products. These volatile substances are carried away by the airflow, thereby achieving the removal of the etched material. The generation process involves various types of collisions: simple ionization, dissociative ionization, and associated dissociative ionization [6].

# 4. Case Analysis

## 4.1 Lithography experiment analysis

The lithography machine is one of the core equipment in semiconductor manufacturing. It is composed of key components such as a light source, mask, optical system and wafer stage. To manufacture a high-performance lithography machine, multi-dimensional regulation and optimization are required. For instance, the selection of light source wavelength, the matching of the numerical aperture of the optical system, and the control of the positioning accuracy of the wafer stage are necessary to achieve high-precision pattern transfer. With the advancement of technology, lithography machines have been continuously upgraded and replaced. Lithography machines have gradually transitioned from traditional ultraviolet lithography to extreme ultraviolet lithography. This progress can meet the requirements for the fabrication of integrated circuits with smaller feature sizes and provides technical support for the production of advanced process chips [7].

The performance optimization of the light source system in the lithography machine is the key to improving the accuracy of the lithography process. The experiments conducted by Dong Jia and others significantly enhanced the output stability and wavelength adjustment accuracy of the light source by optimizing the structure and parameters of the optical components and improving the control algorithm. The experiment focused on improving the wavelength accuracy of the light source system of the lithography machine. By optimizing the structure of optical components and upgrading the control algorithm, precise closed-loop control over the light source current, temperature and wavelength was achieved. The experimental results show that the wavelength control error has been significantly reduced from ±2 nm to ±0.1 nm. The system stability has been significantly enhanced, and it also possesses remote monitoring and real-time control functions, providing a reliable light source guarantee for high-precision lithography processes [8].

The experiments conducted by Li Jun and others focused on the influence of lithography process parameters on depth of field (DOF).The experiment employed a statistical screening method to systematically investigate seven key parameters: pre-drying temperature (SB), gel thickness (CT), development agitation (AG), post-exposure baking (PB), development temperature (TE), development time (TI), and development solution concentration (CO). The experimental data indicate that the concentrations of the developing solution (CO), the agitation during development (AG), the thickness of the gel (CT), and the development time (TI) have the most significant impact on DOF. The average differences in DOF between the high and low levels of these parameters are 1.50 μm, 1.50 μm, 1.35 μm, and 1.20 μm, respectively. In contrast, the effects of pre-baking (SB) and post-exposure baking (PB) on DOF were relatively small (with differences of -0.75 μm and -0.45 μm respectively), which is different from the traditional understanding. The results show that parameters such as developer solution concentration, film thickness, and development time have significant effects on the depth of focus. An increase in numerical aperture can to some extent alleviate the negative impact of process parameter fluctuations on the consistency of line width, thereby improving the transfer accuracy of the photolithography pattern and the overall process stability [9].

The experimental study conducted by Klaus Zimmer et al. has verified the feasibility of the laser ablation technology. The photomask for the lithography process was fabricated on a silicon wafer coated with polyimide (PI), and the ablation was carried out using different wavelengths (193 nm, 248 nm, 308 nm) of excimer lasers. The results show that laser ablation successfully achieved graphic transfer through a combination of thermal, mechanical and ablation effects. When incident vertically, the process is similar to that of ion beam etching, featuring common characteristics such as simultaneous etching of the mask and the substrate, and shadow effect; while when incident at an angle, additional morphological control factors are introduced. This technology offers an effective non-contact solution for high-precision micro-nano processing, providing the feasibility of integrating the photolithography and etching steps. [10]

## 4.2 Etching experiment analysis

Optimizing the key parameters of the wet etching process can significantly improve the uniformity of silicon etching. The experiment conducted by Zhufusheng et al. employed a dual heat exchanger temperature control system to keep the temperature fluctuation of the etching solution within ±1℃, effectively suppressing the rate drift

caused by the heat release during the reaction. Through the design of non-uniform aperture uniform flow plate and the structure of double-sided overflow channel, the flow field was made to be laminarized, and the vortex disturbance was reduced. The experiment shows that combining parallel vibration of the wafer (at a frequency of 20-30 Hz) with rotation (at a speed of 10-15 rpm) can effectively eliminate bubbles and improve the reaction uniformity, increasing the uniformity of etching within the wafer by approximately 40%. Through the collaborative optimization of multiple parameters, a significant improvement in the uniformity of etching within the wafer was achieved, providing effective technical support for high-precision semiconductor manufacturing processes [11].

The stability of wafer temperature in the dry etching process directly affects the etching rate and uniformity. The experiments conducted by Zhao Yang and others demonstrated that the clamping voltage of the electrostatic suction cup and the hydrogen pressure have the greatest impact on temperature, capable of causing a maximum temperature fluctuation of 85°C.When the RF power exceeds 150 W, the ion bombardment intensifies, causing the wafer temperature to rise to 45°C. The wafer warpage is also a factor that cannot be ignored. When the warpage reaches 155 μm, due to poor contact and hydrogen leakage, the wafer temperature significantly increases, and the in-pixel uniformity deteriorates to 6.43%.In contrast, the influence of the upper RF power and the lower electrode cooling temperature is relatively small, with the variation ranges being 10°C and 25°C respectively. These results indicate that in the actual process, it is necessary to prioritize controlling the parameters of the electrostatic suction cup and the wafer flatness in order to maintain stable etching performance [12].

Dominic Stangier et al. investigated the etching process characteristics based on medium-frequency bias, the basic AEGD and its upgraded versions. The experiment selected ultra-fine-grained hard alloy as the substrate and conducted a systematic comparison in an argon gas environment at 400°C.The upgraded AEGD etching process achieves precise control of process parameters by improving the anode current configuration and enhancing the plasma source. The research found that technology, by optimizing the spatial distribution of plasma, significantly improved the etching uniformity, ensuring that the subsequently deposited AlTiN coating exhibited excellent adhesion at all positions on the substrate. The upgraded AEGD etching process outperforms the traditional methods in terms of plasma density control and spatial distribution uniformity, providing a more effective etching pre-treatment solution for PVD coating preparation. [13]

## 5. Challenges and Development

In the current technological context, lithography and etching technologies are the core forces that support the continuous miniaturization of integrated circuit manufacturing towards smaller dimensions. Their own processes also face a series of technical challenges. In the field of lithography, extreme ultraviolet lithography technology has achieved mass production application, but it is still limited by three key factors: the stability of available power, the high cost in the manufacturing process, and the difficulty in controlling random defects during the preparation process. As the resolution of lithography continues to increase, the three-dimensional effect becomes more prominent, resulting in more prominent imaging deviation problems. This directly leads to an increase in the computational difficulty of lithography, causing the complexity of optical proximity effect correction to increase exponentially. In the etching field, the core technical challenge focuses on the precise transfer of three-dimensional device structures. How to maintain the verticality of the morphology, avoid deformation of key dimensions, and effectively control the electrical damage caused by plasma to the device when etching devices with extremely high aspect ratios, is the current technical difficulty that needs to be overcome. In addition, the requirements for the coordinated matching between the two process steps of lithography and etching also increase with the upgrade of the process. This is because the pattern errors in the lithography process will be further amplified during the subsequent etching process. Therefore, the load effect and selectivity ratio of etching, among other parameters, must be incorporated into the unified consideration of lithography and mask optimization. This places higher demands on the integration of the entire process and the allocation of error budgets.

In the future, the advancement of lithography and etching technologies will increasingly rely on cross-disciplinary collaborative innovation. At the lithography level, high numerical aperture EUV equipment will be gradually put into use. To further break through the resolution limit, technical paths such as hybrid patterning, nanoimprinting, and bottom-up molecular self-assembly are also being actively explored. At the etching level, the technical objective will focus on achieving nanoscale morphology control and ultimate selectivity. The combination of pulsed plasma, reactive ion etching and atomic layer etching technologies is expected to enable precise control of the material removal rate and effectively suppress damage. In the future, the process barriers of lithography and etching will show a trend of deep integration. By establishing a “design - lithography - etching” joint simulation model for simulation experiments, precise predictions and compensation for the graphic deformation caused by etching can

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be made before the wafer fabrication, achieving closed-loop optimization.

## 6. Conclusion

Lithography and etching are the core processes in semiconductor manufacturing, directly influencing the performance of integrated circuits. During the lithography process, optimizing the light source system can enhance the accuracy of wavelength control, thereby ensuring the quality of pattern transfer. Among these, the concentration of the developing solution, the thickness of the photoresist, and the developing time have a significant impact on the depth of focus. The effects of pre-baking and post-exposure baking are relatively weak, while increasing the numerical aperture of the optical system can effectively improve the consistency of line width. In the etching process, wet etching improves etching uniformity by controlling temperature, optimizing the flow field, and regulating the movement of the wafer. Dry etching requires precise control of the parameters of the electrostatic suction disk and the flatness of the wafer to maintain stable etching quality. In summary, the progress in integrated circuit manufacturing requires collaborative optimization of lithography and etching processes, with a focus on the regulation of the developing process, precise control of the photoresist thickness, and the parameters of the electrostatic suction disk, in order to effectively improve manufacturing accuracy.

Future related research focuses on exploring the collaborative mechanism of lithography and etching processes. By deeply analyzing the interaction between the two, improving parameter configurations, and providing theoretical support for collaborative optimization. On this basis, further develop an intelligent control system based on real-time monitoring to achieve dynamic feedback and precise adjustment of process parameters, and enhance process stability. At the same time, strive to innovate the architecture of etching equipment and the process material system. Through the optimized design of equipment structure and the application of new materials, break through existing technical bottlenecks and provide theoretical support for the development of the next-generation semiconductor manufacturing technology, and overcome technical challenges.

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