Research on Advanced Photolithography Technology in Semiconductor Processes

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Abstract. This paper explores the research progress in advanced lithography techniques for semiconductor manufacturing. As integrated circuit (IC) process nodes advance, traditional optical lithography faces dual challenges of resolution limitations and rising costs. To address these challenges, advanced lithography techniques such as electron beam lithography (EBL) and X-ray lithography (XRL) have been developed. EBL is categorized into direct-write and projection types. Direct-write EBL offers high precision but low throughput, making it suitable for small-batch production, while projection EBL significantly improves throughput. XRL features high resolution and large depth of focus (DOF), but suffers from mask fabrication difficulties and high equipment costs. The paper also analyzes factors affecting yield in lithography, such as proximity effects, and proposes correction methods including exposure parameter adjustments, Optical Proximity Correction (OPC) techniques, and multi-electron beam lithography (MEBL). Finally, the advantages and disadvantages of different lithography technologies are analyzed. It is concluded that EBL achieves high resolution but has low throughput, whereas XRL provides high resolution and large DOF but faces challenges in mask fabrication and high equipment costs..

Keywords: Semiconductor Lithography, Electron Beam Lithography , X-ray Lithography, Extreme Ultraviolet Lithography.

1 Introduction

Moore's Law states that the number of transistors on an integrated circuit doubles approximately every 18 to 24 months. Between 1975 and 2015, key parameters of ICs—including transistor count, frequency, and core number—increased from magnitudes of 101 to 106, 103, and 102 respectively. However, as IC process nodes advance, traditional optical lithography faces two fundamental physical limitations: Firstly, constrained by the optical diffraction limit, its resolution and the physical limits of the process factor struggle to support the patterning requirements for smaller feature sizes. Secondly, the introduction of compensation techniques like multiple patterning significantly increases process complexity and manufacturing costs, making traditional lithography inadequate for the cost and technical demands of modern processes. Against this backdrop, advanced lithography technologies such as EBL and XRL have been developed to address the escalating costs and process complexity. This paper compares

S. Zhang (ed.), *Proceedings of the 2025 International Conference on Electronics, Electrical and Grid Technology (ICEEGT 2025)*, Advances in Engineering Research 292,
https://doi.org/10.2991/978-94-6463-986-5_19

the technical parameters and process compatibility of different lithography technologies, focusing on their relative strengths and weaknesses, and explores how cross-utilization of these technologies can enhance lithographic precision, production efficiency, and reduce industrial costs.

2 Theoretical analysis of advanced lithography technologies

2.1 Electron beam lithography (EBL) technology

EBL equipment essentially reverses the operation of a scanning electron microscope (SEM), using it for writing instead of reading. Consequently, its field of view and throughput are constrained by this operational principle. Similar to an SEM, an EBL system consists of three fundamental components: an electron gun, a vacuum system, and a control system. [1] A high-energy electron beam generated by a thermal field emission (TFE) or cold field emission (CFE) electron gun is focused through an electromagnetic lens system. Scanning coils then precisely control the beam to expose a photoresist-coated substrate according to the desired pattern. The underlying principle involves the interaction between electrons and the photoresist. The primary EBL techniques in use today are direct-write EBL and projection EBL.

Direct-write EBL involves directly scanning a focused high-energy electron beam point-by-point across the photoresist-coated substrate surface for exposure. It requires no physical mask; the beam path is controlled directly by a computer to generate the pattern. Apart from some niche applications, direct-write EBL suffers from low throughput, hindering its adoption in large-scale manufacturing.

Angle-limited scattering projection electron beam lithography (SCALPEL) is a more promising technique for production applications. Projection exposure systems work by illuminating a broad electron beam onto a mask. The pattern on the mask is then projected onto the wafer through apertures in the mask structure. This principle is analogous to optical lithography. Crucially, electron beams do not suffer from optical diffraction effects like light, enabling much smaller patterns and significantly higher integration density. [2].

2.2 X-ray lithography (XRL) technology

XRL boasts advantages of high resolution, large depth of focus (DOF), and potentially high throughput, positioning it as a highly promising next-generation lithography (NGL) technology. While optical lithography remains dominant today, the adoption phase for NGLs like XRL has been delayed. However, driven by the robust growth of the information and communication market, high-frequency and high-speed compound semiconductor ICs are rapidly developing. Within this context, XRL is widely regarded with significant potential. XRL utilizes high-energy X-rays penetrating a mask to induce chemical changes in the photoresist. Subsequent development creates the desired micro/nano structures. A typical XRL system comprises an X-ray source, a mask, photoresist, and developer solution. Currently, the two main types of XRL are proximity printing and projection printing.

The principle of proximity XRL involves parallel-incident X-rays passing through a 1:1 X-ray mask directly onto the photoresist surface for exposure. A proximity XRL system primarily consists of an X-ray mask, photoresist, a stepper, and an X-ray source.

For proximity XRL, the pattern received by the system is nearly identical to the pattern developed on the photoresist. However, X-ray masks are susceptible to pattern distortion. Causes of distortion include positioning errors related to mask fabrication using EBL, non-uniform mask clamping during exposure, stresses in the mask membrane, and differences in the coefficients of thermal expansion (CTE) between the membrane materials. Geometric optics analysis yields the distortion expression:

$$r_w = r_m + G\frac{r_n}{D} \tag{1}$$

Therefore, fundamental requirements for XRL masks include: the membrane substrate must exhibit good transmittance to both X-rays and visible light, and possess a high elastic modulus to ensure sufficient strength and mechanical stability, making the mask robust with low stress and minimal deformation. The absorber material must have a high X-ray absorption coefficient and sufficient thickness to ensure effective masking during exposure [3].

Projection X-ray Lithography (PXL) is a technique that uses an X-ray source and an optical system to project and demagnify the pattern from a mask onto the wafer surface. This system must utilize soft X-rays. A typical PXL system centers around a plasma-based X-ray source, emitting X-ray beams that work in conjunction with an excimer laser beam. The radiation is conditioned by condenser optics and then enters a reflective, spherical imaging system for reflection and focusing. Further energy concentration is achieved through additional focusing elements. Finally, the high-precision radiation exposes photoresist-coated silicon wafers, creating the fine patterns. The entire system relies on the coordinated action of multiple optical elements to achieve high-resolution lithography.

In the soft X-ray wavelength range (1–30 nm), the refractive index of any material is close to 1, and absorption is significant. Consequently, the optical systems for soft X-ray projection lithography differ fundamentally from the transmission optics used in conventional visible-UV lithography and must employ reflective systems [4]

3 Factors affecting yield in lithography and correction methods

3.1 Proximity effect in electron beam lithography

The proximity effect in EBL exposure arises from the scattering of incident electrons within the resist and substrate. This scattering causes electrons to deviate from their original path, leading to non-uniform energy deposition in the resist, lateral spreading of the exposure, pattern distortion, and ultimately, reduced resolution [5].

Exposure parameter adjustment. Under low acceleration voltages (1–10 kV), dose modulation can be applied. This involves adjusting the exposure dose in different areas based on pattern density. For instance, reducing the dose in dense areas compensates for overexposure caused by scattered electrons, while increasing the dose in isolated areas ensures sufficient exposure. Alternatively, multiple exposures of the same area can be performed, incrementally correcting edges by adjusting focus or dose to reduce cumulative errors.

Optical proximity correction (OPC) technology. The fundamental principle of OPC is to modify the mask pattern so that the final printed image, considering optical proximity effects, more closely matches the design intent. Specifically, OPC adjusts mask pattern edges—through techniques like edge biasing, line thinning, or line thickening—to compensate for proximity effects. Based on the correction strategy, OPC is mainly categorized into two types: Rule-Based OPC (RB-OPC) and Model-Based OPC (MB-OPC). [6]

Simply put, RB-OPC pre-deforms the design pattern based on empirical rules. Examples include adding "serifs" or "hammerheads" to right angles to prevent rounding caused by diffraction. The advantages of RB-OPC are its fast correction speed and low computational cost. Its limitations lie in the finite coverage of rules, difficulty handling complex 2D patterns, and the high cost of re-establishing rules if process conditions change [6].

MB-OPC utilizes optical and resist models to simulate exposure effects and automatically adjusts the mask pattern (e.g., line widths or corner shapes) to counteract proximity effects.

Advanced technology applications. Multiple Patterning Technology (MPT) decomposes complex IC patterns into multiple, simpler exposure layers processed sequentially. It effectively breaks the resolution limits of traditional lithography. Its main advantages are threefold: Firstly, reducing pattern complexity per exposure significantly diminishes optical proximity effects and diffraction interference, enabling feature sizes below the optical wavelength limit. Secondly, optimizing the process window for each step enhances exposure depth of focus (DOF) and critical dimension uniformity (CDU), controlling overlay accuracy within 1-2 nm, thereby improving yield. Finally, MPT leverages existing deep ultraviolet (DUV) lithography tools, saving approximately 40% in equipment investment compared to extreme ultraviolet (EUV) lithography, providing a cost-effective transition for advanced node development. These advantages stem from its "divide and conquer" strategy overcoming lithography equation limitations and its methodological innovation in layered process parameter optimization.

Extreme Ultraviolet Lithography (EUVL):As semiconductor device sizes shrink, traditional lithography encounters physical limits, necessitating shorter wavelength light sources. EUVL theory was proposed and initially researched in the 1980s-1990s. In 1997, the EUV LLC consortium was formed in the US, uniting national labs to advance EUV R&D. Post-2010, ASML (Netherlands) became the primary developer of EUV scanners. By 2016, ASML delivered the first production-worthy EUV lithography system. In EUVL, light with a wavelength of 13.5 nm generated by the source irradiates the photoresist through a reflective mask, inducing specific chemical reactions that alter the resist's solubility in developer, forming the lithographic pattern upon development. [7] Due to the extremely short 13.5 nm wavelength, diffraction effects are minimized, allowing EUVL to pattern finer circuit features, enabling progression from 7nm and 5nm nodes to 3nm and below. The smaller wavelength allows denser packing of components on microchips, resulting in faster processing power. Thus, EUVL enables faster computer processors. The technology holds potential for economic sustainability and finds applications across nearly all fields, including engineering and medicine. Another advantage of EUVL is cost-effectiveness in many patterning processes due to lower power consumption and fewer required exposure steps. [8] Currently, EUVL is on track and expected for implementation at the 22nm half-pitch node and beyond. Designs employing anamorphic optics with eight mirrors will achieve numerical aperture (NA) values exceeding 0.7. Combined with advanced illumination techniques, this will enable EUVL to surpass the 11nm half-pitch currently targeted for EUV infrastructure development. The design and implementation of next-generation pre-production tools are steadily progressing. [9]

3.2 Multi-electron beam lithography (MEBL)

Section 3.1 introduced several methods to reduce the impact of the proximity effect and improve throughput and precision, but those focused on single-beam EBL. Beyond single-beam EBL, Multi-Electron Beam Lithography (MEBL) can significantly enhance throughput.

MEBL is a maskless direct-write technology that forms high-precision patterns directly on the wafer's photoresist using multiple electron beams scanning in parallel. Its core objective is to overcome the resolution and throughput limitations of traditional lithography, making it particularly suitable for small-batch, high-precision device manufacturing. MEBL systems can be realized in different ways: One method uses a single electron gun and an aperture array, where the single beam is split into multiple beams after passing through the apertures. Another method employs multiple electron guns and electron columns to generate the beams. After the beams pass through a blanking plate, their deflection amplitude is controlled by varying voltages on deflection electrodes, enabling precise multi-beam exposure control. Multi-beam technology is another approach to increase writing throughput. In MEBL systems, the writing structure is discretized into pixels, similar to Gaussian beam lithography. Multiple electron beams writing simultaneously multiply the effective throughput [10].

4 Analysis of advantages and disadvantages of different lithography technologies

4.1 4Analysis of electron beam lithography (EBL)

According to the Rayleigh criterion, the resolution of lithography is given by R=k_1 λ / N_A, where NA is the numerical aperture of the optical lens, λ is the exposure wavelength, and k1 is the process coefficient [5]. The de Broglie wavelength of electrons is far shorter than that of visible light, and even shorter than EUV light. Therefore, the theoretical resolution limit of EBL is much higher than that of traditional optical lithography. Furthermore, direct-write EBL does not require masks or complex optical systems; instead, it focuses the electron beam into an extremely fine spot using electromagnetic lenses, directly writing ultra-fine patterns onto the resist. Direct-write lithography completely eliminates expensive masks and reticles, meeting the demands for 3D structures and customized designs by directly manipulating laser or particle beams in three-dimensional space [10]. However, direct-write EBL exposes patterns pixel-by-pixel through point-by-point scanning of a focused electron beam across the sample surface. This "single-point writing" mode, analogous to drawing with a fine pen tip stroke by stroke, cannot achieve the parallel exposure inherent in optical lithography or projection EBL. Even if the exposure time per pixel is very short, the total time for complex patterns increases exponentially. For example, exposing a 1 cm^2 area might take several hours or even days. Other factors contributing to the slowness of direct-write EBL include: the serial scanning nature preventing parallelization; the need for low beam currents to achieve high resolution, prolonging exposure times; delays accumulating from electromagnetic deflection and mechanical stage movements; additional time required for proximity effect compensation; and vacuum maintenance and system calibration occupying productive time. These factors collectively limit its efficiency. Consequently, direct-write EBL is primarily restricted to R&D, mask fabrication, or small-batch production. Regarding projection EBL, like direct-write, it utilizes high-energy electrons for exposure, thus avoiding optical diffraction limits and achieving high resolution. Compared to direct-write EBL, projection EBL projects the entire pattern from a mask in a single exposure step, eliminating point-by-point writing and dramatically increasing throughput.

Therefore, as the most widely used direct-write and high-resolution patterning tool in top-down nanofabrication, EBL offers superior resolution, density, sensitivity, and reliability. Due to the much shorter wavelength of electrons compared to light, EBL enables finer patterning. Additionally, EBL systems do not require complex optics or costly photomasks, making them more cost-effective for small-batch, customized, and research applications. Although EBL's writing speed is relatively slow, its high resolution and reliability make it an indispensable tool for nanofabrication and scientific research. [11].

4.2 Analysis of X-ray lithography (XRL) technology

X-rays typically have wavelengths between 0.01–0.1 nm, orders of magnitude shorter than visible or UV light. This extremely short wavelength minimizes diffraction effects, granting XRL very high resolution, capable of achieving sub-10nm resolution. Furthermore, the short wavelength reduces scattering within the photoresist, lessening the proximity effect and resulting in sharper pattern edges. However, X-ray masks require absorbers made of high-atomic-number materials (like gold or tungsten) to effectively block X-rays, and the supporting membrane must be extremely thin. This makes X-ray mask fabrication exceptionally challenging. Generating X-rays requires high-intensity sources like synchrotrons or plasma sources, leading to large, complex, and expensive equipment..

5 Conclusion

This paper systematically explores the core principles, technical challenges, and practical application potential of advanced lithography technologies, primarily EBL and XRL. Research indicates that EBL, with its sub-nanometer resolution, demonstrates unique advantages in R&D and small-batch production. However, its point-by-point scanning mode results in low throughput, limiting its application in high-volume manufacturing. Projection EBL significantly enhances efficiency through mask-based parallel exposure but still requires overcoming key issues like proximity effects. XRL, benefiting from its extremely short wavelength, offers the dual advantages of high resolution and large depth of focus (DOF). Nevertheless, its industrialization is hindered by significant challenges in mask fabrication and prohibitively high equipment costs. The study further analyzes factors affecting yield and proposes effective correction methods—such as dose modulation, OPC techniques, and multi-electron beam parallel exposure—to optimize pattern fidelity and production efficiency. Additionally, EUVL, as an emerging technology leveraging its 13.5 nm wavelength to break traditional optical limits, has seen gradual adoption in sub-7nm processes, establishing itself as a crucial direction for next-generation lithography.

The core significance of this research lies in providing theoretical support and technical pathways for the semiconductor industry to overcome physical limits. Future research should focus on multi-technology integration and cross-disciplinary innovation. Examples include developing low-cost X-ray mask materials, optimizing parallel control algorithms for MEBL, or integrating AI to accelerate OPC correction workflows. Simultaneously, exploring novel light sources and reflective optical systems is essential to further enhance the numerical aperture (NA) and throughput of EUVL.

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