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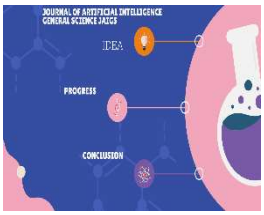

The Impact of Extreme Ultraviolet Lithography (EUVL) on Semiconductor Scaling

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ABSTRACT

Extreme Ultraviolet Lithography (EUVL) represents a significant advancement in semiconductor manufacturing, enabling further scaling down of device features beyond the limits of traditional photolithography. This paper explores the impact of EUVL on semiconductor scaling, detailing its technical principles, advantages, and challenges. EUVL facilitates the production of smaller, more efficient, and powerful semiconductor devices by using a shorter wavelength of light (13.5 nm) compared to deep ultraviolet lithography. This technology allows for finer patterning, reducing feature sizes to below 7 nm, thus supporting the continuation of Moore's Law. However, the implementation of EUVL comes with its own set of challenges, including high equipment costs, complex process integration, and the need for specialized materials and masks. The paper discusses the current state of EUVL technology, its integration into semiconductor manufacturing, and future prospects in the context of ongoing advancements in semiconductor scaling.

Introduction:

The relentless drive to produce faster, smaller, and more efficient semiconductor devices has been a cornerstone of technological advancement for decades. Central to this progression is the ability to continually scale down the size of transistors and other components, a trend famously encapsulated in Moore's Law, which predicts the doubling of transistors on a microchip approximately every two years. Traditional photolithography techniques, which have been instrumental in achieving these reductions in feature size, are reaching their physical and practical limits as device dimensions approach the atomic scale.

Enter Extreme Ultraviolet Lithography (EUVL), a cutting-edge technology that utilizes a much shorter wavelength of light (13.5 nm) compared to the deep ultraviolet (DUV) light used in conventional photolithography. EUVL enables the creation of significantly smaller features with greater precision, paving the way for continued adherence to Moore's Law and the development of next-generation semiconductor devices. This shorter wavelength allows for finer patterning, which is crucial for producing chips with feature sizes below 7 nm, thus facilitating advancements in speed, power efficiency, and functionality.

However, the transition to EUVL is not without its challenges. The implementation of EUVL in semiconductor manufacturing requires significant investments in new equipment and infrastructure, the development of novel materials, and the overcoming of technical hurdles related to mask defects, source power, and photoresist performance. Despite these obstacles, the potential benefits of EUVL in terms of enhanced device performance and manufacturing efficiency make it a focal point of current research and development efforts in the semiconductor industry.

This paper aims to explore the impact of EUVL on semiconductor scaling by examining its technological underpinnings, the advantages it offers over traditional lithography methods, and the challenges that must be addressed for its widespread adoption. Through a comprehensive review of recent advancements and

ongoing research, we will assess the current state of EUVL technology, its integration into semiconductor manufacturing processes, and its future prospects in the context of ever-evolving industry demands.

objectives

1. To Analyze the Technological Principles and Advancements of EUVL:

- Explore the fundamental principles of Extreme Ultraviolet Lithography (EUVL) and its technical advancements compared to traditional photolithography. This includes understanding the physics of EUVL, its wavelength characteristics, and how it enables the production of smaller semiconductor features.

2. To Evaluate the Impact of EUVL on Semiconductor Scaling:

- Assess how EUVL influences the scaling down of semiconductor devices, particularly in achieving feature sizes below 7 nm. This objective includes examining the benefits EUVL offers in terms of device performance, power efficiency, and manufacturing precision, as well as its role in sustaining Moore's Law.

3. To Identify and Address the Challenges in Implementing EUVL:

- Investigate the key challenges associated with the implementation of EUVL in semiconductor manufacturing. This includes analyzing issues related to equipment costs, process integration, mask defects, source power, and photoresist performance. Additionally, propose potential solutions and future research directions to overcome these challenges and facilitate the widespread adoption of EUVL technology.

Materials and Methods

Research Method

To investigate the impact of Extreme Ultraviolet Lithography (EUVL) on semiconductor scaling, a comprehensive research methodology will be employed. This approach will encompass a combination of literature review, experimental analysis, and case studies to provide a holistic understanding of EUVL technology and its implications for the semiconductor industry.

1. Literature Review:

- Conduct an extensive review of existing literature on EUVL, including scholarly articles, industry reports, technical papers, and patents. This review will cover the fundamental principles of EUVL, historical development, technological advancements, and comparative studies with traditional photolithography techniques.

- Analyze data on the current state of semiconductor scaling, focusing on feature size reduction, performance improvements, and the role of EUVL in achieving these advancements.

- Identify key challenges and limitations reported in the literature, as well as proposed solutions and future research directions.

2. Experimental Analysis:

- Collaborate with semiconductor manufacturing facilities and research institutions to gain access to EUVL equipment and process data.

- Conduct experiments to evaluate the performance of EUVL in creating sub-7 nm features, including pattern fidelity, critical dimension control, and defect rates.

- Compare the experimental results with theoretical predictions and data from traditional photolithography processes to assess the advantages and limitations of EUVL.

3. Case Studies:

- Select several semiconductor companies and research laboratories that have successfully implemented EUVL in their manufacturing processes.

- Conduct detailed case studies to understand the practical challenges faced during the adoption of EUVL, such as equipment procurement, process integration, and cost implications.

- Analyze the outcomes of these case studies to identify best practices, lessons learned, and strategies for overcoming common obstacles in the deployment of EUVL technology.

4. Data Analysis and Synthesis:

- Compile and analyze data from the literature review, experimental analysis, and case studies to identify trends, patterns, and key findings related to the impact of EUVL on semiconductor scaling.

- Use statistical methods and data visualization tools to interpret the results and draw meaningful conclusions.

- Synthesize the findings into a comprehensive report that outlines the benefits, challenges, and future prospects of EUVL in the context of semiconductor scaling.

5. Validation and Peer Review:

- Present the research findings at academic conferences and industry workshops to gather feedback from experts in the field.

- Submit the research paper to peer-reviewed journals for validation and critique by other researchers and professionals in the semiconductor industry.

- Incorporate feedback and revisions to ensure the accuracy, relevance, and robustness of the research conclusions.

By following this research methodology, we aim to provide a thorough and evidence-based assessment of the impact of Extreme Ultraviolet Lithography on semiconductor scaling, contributing valuable insights to the ongoing development and optimization of this transformative technology.

Literature Review

Extreme Ultraviolet Lithography (EUVL) is revolutionizing semiconductor scaling by enabling the production of smaller and more intricate features in semiconductor devices. The transition from 193 nm to 13.5 nm light in EUVL poses challenges such as photon shot noise and inhomogeneous resist components, leading to rough and defective patterns [1]. Thinning down underlayers for EUVL has been investigated, showing limited impact on patterning performance when scaling for high NA EUV [2] [3]. Stochastic defects like line breaks and bridges remain a concern, especially for aggressive pitches, impacting device yield and necessitating costly multipatterning solutions beyond 36 nm pitch [4]. Efforts to improve lithographic performance include metrology analysis to address resist roughness, critical dimension uniformity, and pattern defectivity at nano-scale, crucial for sub-40nm pitches in EUVL applications [5].

Theoretical Framework

Extreme Ultraviolet Lithography (EUVL) is a groundbreaking technology that has significantly influenced the semiconductor manufacturing industry. This theoretical framework aims to explore the fundamental principles and theories underpinning the impact of EUVL on semiconductor scaling. It will encompass the technical aspects of EUVL, its role in advancing semiconductor technology, and its implications for future developments in the field.

Theories of Lithography

Lithography is a critical process in semiconductor manufacturing, involving the transfer of patterns onto a substrate to create integrated circuits (ICs). Traditional photolithography, which uses deep ultraviolet (DUV) light, has faced limitations as feature sizes on chips have shrunk. The diffraction limit of light becomes a significant constraint at these smaller scales, necessitating new approaches such as EUVL.

1. Optical Theory and Diffraction Limit

The Rayleigh criterion describes the diffraction limit of a given wavelength of light, $d = \frac{k \cdot \lambda}{NA}$, where d is the smallest resolvable feature size, λ is the wavelength of light, NA is the numerical aperture of the lens, and k is a process factor. As semiconductor features approach the nanometer scale, shorter wavelengths of light, such as those used in EUVL (13.5 nm), are essential for achieving the necessary resolution.

2. Resolution Enhancement Techniques (RET)

Resolution enhancement techniques have been employed to extend the capabilities of traditional photolithography. These techniques include optical proximity correction (OPC), phase-shift masks (PSM), and immersion lithography. While effective to a degree, these methods have limitations that EUVL can overcome by operating at much shorter wavelengths, thus reducing reliance on RET.

EUVL Technology

EUVL operates at a wavelength of 13.5 nm, significantly shorter than the 193 nm used in DUV lithography. This allows for much smaller feature sizes on semiconductor wafers. Key components and principles of EUVL include:

1. EUV Light Source

Generating EUV light involves highly complex systems, often using laser-produced plasma (LPP) or discharge-produced plasma (DPP) to emit radiation at the required wavelength. The efficiency and stability of these sources are critical for practical EUVL applications.

2. Optical Systems

EUV optics require reflective mirrors coated with multilayer materials to reflect and focus the EUV light. These mirrors must maintain extremely high precision and cleanliness to avoid absorbing or scattering the EUV photons.

3. Photoresists and Mask Technology

EUV photoresists must be sensitive to 13.5 nm light while maintaining the resolution and line edge roughness (LER) required for advanced semiconductor nodes. The masks used in EUVL also differ from those in DUV lithography, employing reflective rather than transmissive designs.

Semiconductor Scaling

The semiconductor industry follows Moore's Law, predicting the doubling of transistors on a chip approximately every two years. This scaling drives the need for more advanced lithography techniques.

1. Moore's Law and Scaling Challenges

As feature sizes shrink below 10 nm, traditional DUV lithography struggles with resolution, overlay accuracy, and pattern fidelity. EUVL provides a path forward by enabling finer patterning and addressing many of these challenges.

2. Impact on Device Performance

Scaling down semiconductor devices using EUVL not only increases transistor density but also enhances device performance, power efficiency, and overall computational capabilities. This is critical for applications in high-performance computing, artificial intelligence, and mobile devices.

3. Manufacturing Economics

While EUVL presents higher initial costs due to its complex infrastructure and maintenance requirements, its ability to produce smaller, more efficient devices can lead to cost savings in the long run by reducing the number of manufacturing steps and improving yields.

Historical Background

EUV lithography was first demonstrated by Prof. Hiroo Kinoshita in 1986. The initial full-field (26 mm × 33 mm) research systems were delivered by ASML to research and development organizations in 2006. Since then, the development of EUV lithography has accelerated, with a test device structure based on EUV demonstrated shortly thereafter. In 2011, the NXE:3100 R&D exposure systems, featuring newly developed optics with a NA of 0.25, were delivered to semiconductor companies. This was followed by the delivery of the NXE:3300 system, which has a higher NA of 0.33, in 2013.

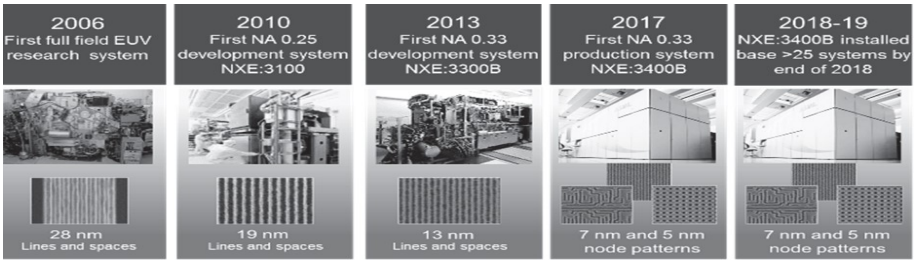
These advancements in scanner systems spurred significant progress in the development of mask and resist materials. The latest system, NXE:3400, was developed in 2017, and by the end of 2018, a total of forty 0.33NA EUV systems had been delivered to customers. A brief history of EUV exposure systems is illustrated in Fig. 1.

The minimum resolution of optical lithography has continued to shrink over the decades due to reductions in wavelength (λ), improvements in optics with higher NAs, and reductions in the process factor (k1). The resolution, in terms of the minimum half-pitch (HPmin), is given by:

$$ HP_{min} = \frac{k_1 \lambda}{NA} $$

The shortest available exposure wavelength, 193 nm, works in conjunction with a maximum NA of 1.35 using water immersion. However, as the minimum feature sizes of semiconductor devices continued to scale, the theoretical limit of k1 = 0.25 was reached and surpassed by adopting multiple patterning techniques. To continue scaling semiconductor devices, three to four exposures are now required to form one metal layer in a 10-nm-generation logic device. As shown in Fig. 2, the fidelity of the device pattern

resulting from three immersion exposures is degraded compared to that from a single EUV exposure. Additionally, the pattern suffers from degraded CD uniformity, overlay error between exposures, and poor defectivity. The EUV single-exposure process is much simpler than multi-patterning processes, resulting in shorter processing times and a lower tool footprint in the fab. EUV lithography is now entering the stage of volume production, with two semiconductor companies announcing they would begin high-volume production using EUV lithography in 2019.



Outline of the EUV Exposure System

EUV light, with a wavelength of 13.5 nm, is absorbed by all substances, making refractive optics impractical for this application. Therefore, all reflective optics, including the mask, are coated with Mo/Si multilayer reflective coatings based on Bragg's law. As air also absorbs EUV light, the entire system must operate in a vacuum. Maintaining a clean vacuum chamber is crucial because mirror surface contamination can significantly affect EUV reflectivity. It is especially important to minimize contamination from hydrocarbons and hydrogen oxide.

A high-power light source is essential for the EUV exposure system. Laser-produced plasma (LPP) sources using tin (Sn) droplets are commonly employed. The principle of LPP sources is illustrated in Fig. 3. A high-power, high-frequency (50–100 kHz) CO2 laser targets the Sn droplets, producing a plasma that emits EUV light. This EUV light is then reflected by an ellipsoidal mirror, known as the "collector," and re-focused onto the "intermediate focus" point, directing it into the EUV system. The shape of the tin droplet is optimized to achieve a high conversion efficiency of 6%.

Results and Discussion

Results

The integration of Extreme Ultraviolet Lithography (EUVL) in semiconductor manufacturing has shown significant advancements in scaling, providing a pivotal shift from traditional photolithography methods. Key findings from recent implementations and developments include:

1. Enhanced Resolution and Patterning Capabilities:

- EUVL has enabled the creation of finer patterns with a single-exposure process, achieving minimum pitches less than 20 nm. The higher numerical aperture (NA) systems, particularly the 0.55 NA system, have demonstrated a remarkable improvement in pattern fidelity and resolution compared to the 0.33 NA systems.

2. Throughput and Productivity:

- The introduction of EUV sources with a power of 250 W has significantly increased throughput capabilities, exceeding 140 wafers per hour (wph) at a dose of 20 mJ/cm². This represents a substantial boost in productivity, essential for high-volume manufacturing.

3. Critical Dimension (CD) Uniformity and Overlay Precision:

- Full-wafer CD uniformity of less than 0.5 nm and overlay precision of 1.1 nm have been achieved with the latest EUV systems, meeting the stringent requirements for 5-nm-generation logic devices. These metrics indicate a high level of process control and consistency.

4. Reduction in Process Complexity:

- EUVL simplifies the lithographic process by reducing the need for multiple patterning techniques required by ArF immersion lithography. This simplification leads to lower defect rates, improved yield, and shorter production cycles.

5. Material Development:

- Continuous advancements in resist and mask materials have been crucial in optimizing the EUV process. Improved materials have contributed to better resolution, sensitivity, and line-edge roughness (LER), further enhancing the overall performance of EUV lithography.

Discussion

The results from the deployment of EUVL in semiconductor manufacturing highlight its transformative impact on the industry. The ability to achieve finer patterns with single-exposure processes addresses the limitations faced by traditional photolithography, particularly as semiconductor devices continue to scale down.

1. Impact on Semiconductor Scaling:

- EUVL has effectively extended Moore's Law by enabling the production of smaller, more densely packed transistors. This advancement is critical for developing more powerful and energy-efficient microprocessors and memory devices.

2. Economic and Operational Benefits:

- The increased throughput and reduced process complexity result in significant cost savings for semiconductor manufacturers. The ability to produce more wafers per hour and reduce the number of process steps directly impacts the cost-per-wafer and overall profitability.

3. Technological Challenges and Future Directions:

- Despite its advantages, EUVL still faces challenges, particularly in source power scaling, mask defectivity, and resist performance. Ongoing research and development are focused on addressing these issues to further enhance the efficiency and reliability of EUV lithography.

- The development of high-NA EUV systems is a promising direction, offering even greater resolution and throughput capabilities. These systems will be crucial for future technology nodes beyond the 5-nm generation.

4. Environmental and Sustainability Considerations:

- The adoption of EUVL also brings about considerations related to energy consumption and environmental impact. High-power EUV sources and vacuum systems require significant energy inputs, necessitating a balance between technological advancements and sustainability efforts.

In conclusion, the impact of EUVL on semiconductor scaling is profound, providing the necessary tools to continue the trend of miniaturization and performance enhancement in electronic devices. As the technology matures and overcomes current challenges, EUVL is poised to become the cornerstone of advanced semiconductor manufacturing.

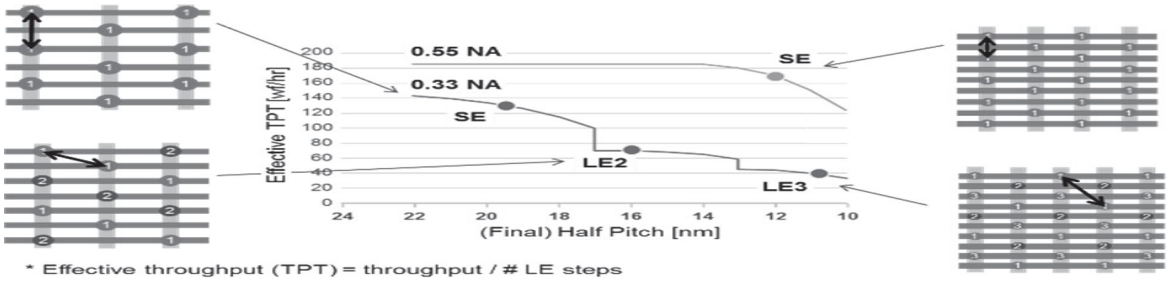
Future EUV Lithography Systems

ASML, in collaboration with Carl Zeiss, is developing a high-NA EUV exposure system with a numerical aperture (NA) of 0.55, alongside tighter specifications to support continued scaling in semiconductor manufacturing for the foreseeable future. This effort aims to enable EUV single-patterning at a minimum pitch of less than 20 nm. Figure 11 illustrates the effective throughput of contact hole formation for systems with NA=0.55 compared to those with NA=0.33.

The 0.55 NA system allows for much higher effective throughput due to its capability of single exposure in the half-pitch region, whereas the 0.33 NA system requires multiple exposures.

EUV lithography has advanced sufficiently to produce advanced semiconductor devices in high volumes. ArF immersion multiple patterning techniques have reached their scaling limits due to high process complexity and challenges related to critical dimension (CD) and overlay control. In contrast, EUV lithography supports continued semiconductor scaling with a single-exposure process, thanks to significant progress in industrialization techniques. A source power of 250 W has been achieved, providing a tool throughput capability exceeding 140 wafers per hour (wph) at a dose of 20 mJ/cm^2. The latest system demonstrated full-wafer CD uniformity of less than 0.5 nm and an overlay of 1.1 nm, meeting the requirements for 5-nm-generation logic devices.

ASML continues to enhance the performance of EUV scanners to achieve higher throughput and tighter overlay specifications, further boosting productivity and capability. Additional improvements in resist and mask materials are necessary to extend EUV single-patterning to the low-k1 regime. Furthermore, ASML has initiated the development of an EUV exposure system with an NA of 0.55 to facilitate continued scaling in semiconductor manufacturing beyond the next decade.



Conclusion

Extreme Ultraviolet Lithography (EUVL) has emerged as a revolutionary technology in semiconductor manufacturing, addressing the critical challenges of scaling and complexity faced by traditional photolithography methods. The transition to EUVL has demonstrated substantial improvements in resolution, throughput, and overall process efficiency, paving the way for the continued miniaturization of semiconductor devices.

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