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Research on the current research status and future development trend of extreme ultraviolet

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Abstract. Extreme Ultraviolet (EUV) lithography is pivotal in semiconductor manufacturing and attosecond metrology. This paper delves into the current research status and future development trends of EUV, aiming to offer a comprehensive understanding and predictions for this technology's evolution. Considering the challenges in applying EUV in chip manufacture, we will discuss advanced methods such as metalenses, phase-shifting masks, EUV transient grating spectroscopy, and negative tone development (NTD) processes to address issues in photolithography. Additionally, this article employs a methodical literature review and analysis. Presently, EUV lithography machines with a numerical aperture (NA) of 0.33 have achieved mass production of 5nm logic chips. Nevertheless, generating a more stable EUV light source and enhancing the focusing ability and power of the light source remain critical challenges requiring resolution.

Keywords: EUV lithography, EUV source, EUV mask, stochastic issues

1. Introduction

As is widely recognized, chips and integrated circuits are pivotal components of modern electronic devices. Since the invention of the integrated circuit, they have been applied across various industries, rapidly transitioning humanity from the industrial age to the information age. Jack Kilby, the inventor of the integrated circuit, was awarded the Nobel Prize in Physics in 2000 for this seminal achievement. Virtually all electronic devices rely on chips, and chip manufacturing technology is a crucial indicator of a country's core competitiveness. In recent years, the rapid emergence of industries such as the Internet of Things and artificial intelligence has surged the demand for high-performance chips, which in turn has necessitated advancements in data processing speed, storage capacity, and energy consumption efficiency. Lithography technology is essential for the realization of these high-performance chips, with Extreme Ultraviolet (EUV) lithography being one of the most critical technologies for manufacturing higher precision chips. To meet the growing demand for chips with enhanced computing power and energy efficiency, developing higher-power laser light sources remains a significant challenge to be addressed. This paper aims to explore feasible methods for enhancing EUV technology. To date, several advancements have been made in EUV light sources, including the fabrication of an EUV metalens with a focal length of 10 millimeters and a numerical aperture of 0.05, which has been used to focus ultrashort EUV light bursts generated by high harmonic generation [1]. Additionally, ASML and Zeiss have developed a 0.55-NA "high-NA" EUV system to enhance resolution [2]. Furthermore, research has been conducted on a high-power EUV free-electron laser (FEL) based on an energy-recovery linac (ERL) [3]. The current development trend in EUV is to further improve lithography resolution and throughput while upholding the progression of Moore's Law. However, the field is confronting critical challenges related to stochastic issues, such as photon stochastic and chemical stochastic [4].

2. Present research status

2.1. EUV light source

In response to Moore's Law, the semiconductor industry has been advancing the development of chips with higher density, necessitating lithography technology with superior resolution. Consequently, EUV lithography has emerged as the most critical method for high-precision chip manufacturing. Central to this technology is the requirement for a high-power, high-stability EUV light source. However, the global adoption of EUV lithography machines has been limited, primarily due to the constraints of the

Laser-Produced Plasma (LPP) EUV light source, which targets Sn droplets. The LPP EUV light source operates on the principle of high-intensity laser interaction with the target material, whereby the absorption layer is heated and vaporized to produce plasma. [5]This process, influenced by inverse bremsstrahlung absorption (IBA), [6]results in continuous heating of the plasma and the emission of ultra-wide spectral radiation. Nevertheless, in 2021, Tsinghua University, in collaboration with several German research institutions, validated the principle of the Steady-State Micro-Bunching (SSMB) EUV light source. [7]The SSMB EUV light source employs laser modulation to bunch electrons, thereby generating EUV light beams characterized by high power, high repetition frequency, and narrow bandwidth. Owing to its exceptional performance, this technology is well-suited for EUV lithography and represents a novel approach to preparing light sources for lithography machines. Nonetheless, the R&D of the SSMB-EUV light source remains in its early stages. To realize its practical application, sustained scientific breakthroughs are essential, alongside cooperation across the entire industrial supply chain. Since the publication of Tsinghua University's research findings in Nature in 2021, they have garnered significant public attention. These findings not only highlight the advancements in China's particle accelerators and synchrotron radiation fields but also hold the potential to provide a technical solution for domestically produced EUV lithography machines.

2.2. EUV mirror

Generally speaking, EUV lithography machines with a light source of 13.5 nm wavelength adopt a reflective optical system, which is determined by the material characteristics of the extreme ultraviolet band, so mirrors are an important component in EUV lithography machines. Due to the extremely high EUV absorption rate, the energy weakens by 40% with each reflection of the mirror. According to industry standards, only about 1% of the EUV light source energy finally reaches the wafer through 10 mirrors, which means that a very high EUV light output is required. Since 2002, the German PTB research group has been investigating the development of a large reflectometer for collector mirrors to advance the creation of high-intensity EUV light sources. This research aims to enhance the feasibility of large-scale condenser mirrors for such light sources. Additionally, at the New SUBARU synchrotron light facility, a research group from the University of Hyogo has constructed a significant reflectometer to measure the reflectance of a reflective mirror with a diameter of 800 mm, intended for use as a collector mirror.[8] The large reflectometer under study is capable of calculating the reflectivity of large collectors, thereby contributing to the improvement of collection efficiency for the implementation of high-EUV-power light sources.

2.3. Refractive lenses for EUV

In common optical systems, such as cameras, telescopes, and traditional ultraviolet lithography techniques, optical elements like apertures and lenses are arranged axially symmetrically along a straight line. This approach is not applicable to EUV rays. Because of the domain of semiconductor photolithography, it deeply relied on short wavelengths, especially in the EUV realm. However, most optical materials exhibit intense light absorption within this wavelength range, leading to a scarcity of viable transmissive components and consequently, a significant loss of light power. It is worth noting that Ossiander et al. have experimentally demonstrated the metalens as an exceptional method for focusing EUV light [1]. This groundbreaking discovery has substantially advanced the development of transmissive optics for the EUV regime.

2.4. EUV transient grating spectroscopy

Laser - induced transient grating (TG) technology is a variant of non-collinear four-wave mixing (FWM), where two short optical pulses of the same wavelength overlap both temporally and spatially in the sample to generate a spatially periodic material excitation. This excitation is probed by the diffraction of a third variable-delay pulse. This method allows for the measurement of heat transfer at the ~10 nm scale. In this measurement, the two samples exhibit different heat transfer mechanisms, and this method can be applied to study other phenomena that display non - trivial behavior at the nanoscale. The results obtained by Peter R. Miedaner and others from the EUV transient grating experiment using coherent magnons in Fe/Gd ferrimagnetic multilayers have revealed the heat - transfer dynamics that can now be studied in-depth [9]. Additionally, they discussed the potential of this new type of experiment in researching structural dynamics, transport phenomena, and magnetism at the nanoscale. Moreover, in the extreme ultraviolet lithography process, this technology can be used to monitor in real-time the physical and chemical changes of photoresist during the exposure process, such as the progress of the photochemical reaction of photoresist, the breakage and recombination of polymer chains, etc. This enables the optimization of lithography process parameters, improves the resolution and accuracy of lithography, and contributes to the manufacturing of chips at smaller scales.

2.5. Phase-Shift Mask Lithography (PSM)

Phase-shift mask lithography is an advanced lithography technology used in the semiconductor manufacturing process to improve the resolution and imaging quality of integrated circuits. It works by introducing a phase shift to the light passing through specific areas of the mask. In a traditional photomask, the pattern is composed of opaque and transparent regions. However, in phase-shift mask lithography, an additional 180 - degree phase shift is usually introduced to some of the transparent regions. When light waves from different regions reach the wafer surface, this causes them to interfere with each other. The constructive and destructive interference patterns enhance the contrast of the light intensity distribution, enabling the creation of finer and more precise patterns on the wafer. Here, we need to mention the Alternating Phase-Shift Mask (Alt-PSM): In this type, adjacent features on the mask have opposite phase shifts, typically 0 degrees and 180 degrees. This creates strong destructive interference at the edges of the features, significantly improving the resolution and reducing the linewidth of the printed patterns. It is commonly used for printing dense patterns such as those in memory chips. To realize the alternating phase - shift mask, Minoru Sugawara et al. proposed a new additive structure composed of ruthenium (Ru), silicon (Si), tantalum nitride (TaN) and molybdenum (Mo) materials [10]. This new structure can achieve a 180-degree phase shift and the same reflectance. Consistency is ensured by appropriately choosing the complex refractive index and multiple interference in each layer. According to their experimental results, this new type of alternating phase-shift mask effectively improves the resolution.

3. Future development trends

How to solve the high-volume manufacturing (HVM) problem and reduce the random constraints are the directions for future research.

Nowadays, Extreme Ultraviolet (EUV) lithography technology can be used for 10-nanometer-generation node manufacturing and more advanced processes. In 2019, EUV lithography technology was finally applied to High-Volume Manufacturing (HVM) to fabricate advanced semiconductor devices. It was a long process from researching EUV technology to implementing it in HVM. One of the key factors in achieving EUV lithography is the selection of EUV photoresist materials. These materials can resolve sub-15-nanometer half-pitches with high sensitivity. However, the performance of EUV photoresists still fails to meet the actual requirements of high-volume manufacturing. Meanwhile, when the feature size and edge control requirements approach the molecular scale, all traditional lithography techniques will be affected by stochastic variations. Even with the latest qualified EUV photoresist materials, the performance of EUV photoresist materials is still insufficient to meet the expected HVM requirements. Some people have proposed that the NTD (Negative Tone Development) lithography process can be used to improve the lithography capabilities of lithography machines [11]. Previously, the negative-tone system referred to the cross-linking system using traditional tetramethylammonium hydroxide (TMAH) developer. However, significant swelling was observed in the cross-linking system with TMAH developer, so it was not suitable for fabricating small critical dimension (CD) patterns. Compared with the positive-tone imaging (PTI) process, the negative-tone imaging (NTI) process offers lower swelling and smoother dissolution behavior, which reduces dissolution stochasticity. Therefore, negative-tone imaging with EUV exposure (EUV-NTI) has a huge advantage in terms of performance. However, the development of this process is still very difficult at present. One of the key issues is the stochastic problem, which includes photon stochasticity and chemical stochasticity, leading to defects. The stochastic issues in EUV lithography are primarily attributed to the low number of photons in the EUV light source, known as "photon shot noise." Despite recent advancements in light source power, stochastic problems remain critical. These issues are not solely due to photon shot noise but also arise from EUV materials and processes, termed "chemical stochasticity" [12]. The challenges associated with chemical stochasticity originate from photoresist materials and lithography processes, material uniformity in thin films, photon capture efficiency, reaction uniformity in thin films, and dissolution behavior with developers. Addressing these stochastic limitations in EUV lithography, which potentially constrain product yield and lithography throughput, represents one of the most significant challenges we aim to overcome. To mitigate the photon stochastic effect, EUV photoresists must be designed to effectively capture more photons, given their inherently low photon count. To enhance photon capture at the source, Toru Fujimori et al. developed "organic high-EUV-absorption materials" that facilitate more efficient photon capture [13]. Experimental results indicate that high-absorption photoresists achieve a 20% dose reduction while maintaining line width roughness (LWR) values. Furthermore, the nano-bridges in high-absorption photoresists are substantially reduced, thereby improving lithography performance due to the mitigation of stochastic problems. The application of "organic EUV high-absorption materials" and innovative technologies and materials aimed at reducing chemical stochasticity is anticipated to be integral to the realization of high-volume manufacturing (HVM) in EUV lithography.

4. Conclusion

This paper has some drawbacks and limitations, because it just only discuss about some specific technology like metalens, phase-shifting mask and EUV transient grating spectroscopy. There are still many of the latest and more pioneering technologies that are not mentioned in this article. However, most of the technical methods are still in the experimental stage and not ready for large - scale commercial application. Of course, this article merely provides some introductions to these technologies and does not delve into their theories and principles. Moreover, this paper only shares some particular trouble we faced now, such as, stochastic limitations and how to HVM. In fact, the problems currently faced by EUV technology are far more than those mentioned in this article. For example, there are issues such as EUV light source loss and high energy consumption. It is hoped that with our continuous in - depth research, these problems can be solved in the near future.

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