Progress and Prospects of Extreme Ultraviolet Multilayer Film Research

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Abstract: Extreme ultraviolet lithography technology has become a key process in the semiconductor manufacturing industry. Owing to the pronounced absorption characteristics and elevated refractive index associated with extreme ultraviolet light, extreme ultraviolet lithography systems necessitate the utilization of optical components that comprise multilayer film structures as mirrors. This configuration is essential to fulfill the stringent requirements for high reflectivity in such applications. This paper adopts a research method of literature reading and analysis, describing the current research status of extreme ultraviolet multilayer films, including the performance of extreme ultraviolet multilayer films, related technologies for preparation, and optimization problems that need to be addressed.This paper further delineates the multilayer film structures that are applicable to this emerging technology, and it anticipates the prospective developmental trajectory of future extreme ultraviolet multilayer films. It can be concluded that the theory of 13.5 nm extreme ultraviolet multilayer films has matured, but difficulties still exist in their practical preparation. In the future, as the performance requirements of integrated circuits continue to increase, EUV multilayer films will develop towards shorter wavelengths of 6.X nm.

Keywords: EUV Multilayer, Multilayer Preparation, Deposition Technology, Multilayer Contamination, Cleaning Technology

1. Introduction

Since the 21st century, the rapid development of the integrated circuit industry has demanded higher operating frequencies and lower power consumption from high-performance chips, necessitating a significant increase in chip integration density. The linewidth precision of circuit patterns is directly influenced by the resolution of the light source, which is closely related to the Rayleigh criterion $R = (k1\lambda)/NA$. Against this backdrop, reducing the wavelength of the light source has become the mainstream technological approach to enhancing resolution. The Dutch company ASML has successfully implemented a 13.5nm EUV light source using liquid tin plasma technology, representing a 14-fold improvement over the 134nm wavelength of ArF immersion lithography, and bringing revolutionary changes to the microelectronics manufacturing industry.

EUV light occupies the spectral region between vacuum ultraviolet and soft X-rays, possessing a wealth of atomic spectral lines, which result in significant absorption characteristics, thereby precluding the use of transmission optical elements. Furthermore, for reflective materials, their refractive index is nearly 1, making it difficult to achieve high reflectivity at normal incidence. Although research has shown that high reflectivity can be theoretically achieved through Bragg

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crystal interference, in practical applications, such as Mo/Si multilayer films, which exhibit the highest reflectivity at 13.5nm and have become a focal point of EUV lithography research, the fragments generated during the fabrication process pose challenges to the performance and longevity of the multilayer films [1]. This area remains a technical gap that urgently needs to be addressed.

This paper aims to systematically review the current research progress in the performance requirements, fabrication techniques, and optimization strategies of EUV multilayer films. On this basis, it also looks ahead to the development direction of the next generation of EUV multilayer films, with the goal of providing theoretical support and technical guidance for further enhancing the efficiency and stability of EUV lithography technology.

2. Multilayer film performance requirements

In order to fulfill the requirements of sophisticated photolithography manufacturing, the multilayer films utilized in extreme ultraviolet light source systems must meet stringent criteria across multiple dimensions.

2.1. High reflectivity

The light source system, including condenser lenses, illumination systems, reflective masks, and projection objectives, is composed of multiple multilayer film mirrors. Even if the reflectivity of each reflective surface is slightly lower than the qualified reflectivity, the total light flux after system reflection will still significantly decrease.

2.2. Peak wavelength matching

The reflection bandwidth of the multilayer film must be kept within a reasonable range. For the Mo/Si multilayer film suitable for 13.5 nm, its bandwidth tolerance range is 0~0.6 nm. The bandwidth deviation of the reflection mirror will affect the quality of the final reflected light wavelength. To ensure that the system has a high light flux, the peak wavelength of the reflection mirror must be strictly matched. The matching error needs to be controlled within $\Delta\lambda < \pm 0.05$ nm [2].

2.3. Surface shape assurance

Extreme ultraviolet lithography technology represents the current cutting-edge manufacturing technology at its limit. The surface roughness of optical elements is closely related to the Bragg diffraction effect. Ensuring the quality of the surface shape is a necessary condition for obtaining good light sources.

2.4. Thermal stability

The operational environment of the extreme ultraviolet light source system is characterized by high temperatures, posing a significant challenge to the multilayer film structure in maintaining stable cycling and preserving distinct interface layers [3]. Therefore, some optical elements, such as condenser lenses in the light source, need to maintain performance in high-temperature environments. To meet this need, the multilayer film must have good thermal stability.

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3. Multilayer Film Preparation Technology

3.1. Magnetron Sputtering Method

Magnetron sputtering technology has significant advantages in the preparation of multilayer films. The method deposits particles with high energy, stable deposition rate, and can control the film thickness to the nanometer level. Due to the dense film layers, high reflectivity, and good peak matching, magnetron sputtering technology has been widely used in the preparation of extreme ultraviolet multilayer films [4]. Various research institutions and companies have developed dedicated magnetron sputtering deposition equipment for the preparation of extreme ultraviolet multilayer films. For example, the Fraun-hofer-IOF institute uses the NESSY developed by Leybold, with a maximum reflective mirror diameter of 650 mm; Nikon has obtained a mirror with a maximum coating diameter of 600 mm through its own developed equipment [2]. The uniformity of the deposited film thickness is currently an important factor in magnetron sputtering preparation. Adjusting the revolution speed of the substrate, adjusting the rotational speed of the rotation system, adding correction baffles, and increasing the target area are common methods for adjusting the uniformity of film thickness. Xu Guohua [5] et al. improved the uniformity of the periodic thickness of the multilayer film by continuously adjusting the speed of the substrate passing over the surface of the target material through high-frequency changes in the orbital velocity. Synchrotron radiation testing results showed that at an incident angle of 5°, the reflectivity of the Mo/Si multilayer film reached 62.2% at the center wavelength of 13.5 nm.

3.2. Electron Beam Evaporation Method

In the process of multilayer film deposition, the electron beam evaporation technology converts electron kinetic energy into internal energy of the target material, that is, by bombarding the target material with an electron beam, causing it to evaporate and deposit on the substrate to form a thin film. In this method, due to the difficulty of low-energy particles overcoming the obstacles between particles, it is easy to increase the surface roughness of the film layer, so it is usually combined with ion beam polishing technology to make the interface smoother. Furthermore, due to the unstable deposition rate of low-energy particles, real-time monitoring technology, such as the method of X-ray reflectivity measurement, is needed to monitor the film thickness [6]. Only a few research institutions, such as FOM-Rijnhuizen, possess the capability to employ this technology for the fabrication of extreme ultraviolet multilayer films.Although the equipment used for evaporative coating is simple, the structure of the deposited film is relatively loose. From a microscopic perspective, the thin film deposited on it has a columnar structure, making it easy for moisture in the air to adsorb and penetrate. Generally speaking, evaporation coating is not the best method for preparing extreme ultraviolet multilayer films [7].

3.3. Ion Beam Sputtering Method

Ion beam sputtering technology has many similar advantages to magnetron sputtering technology, producing high-energy target material particles, and the deposition rate is also sufficiently stable. The reflectivity of the multilayer film prepared by this technology is slightly lower than that of the films prepared by magnetron sputtering and electron beam evaporation, but its defect density is the least, so this technology is a good method for the preparation of mask blank multilayers. The NEXUS-LDD-IBD ion beam deposition system, developed in collaboration between Lawrence Livermore National Laboratory and Veeco Instruments, Inc., is specialized equipment designed for the fabrication of multilayer film mask blanks [8]. Defects generated during the manufacturing process can cause deformation of the multilayer film structure, thereby interfering with the

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reflection effect of the mask. Li Guannan [9] et al. studied the influence of defects on the reflection field of multilayer films, both on the substrate and within the multilayer structure. This provided us with a deeper understanding of the disturbance of defects on the reflection field, and helped optimize the thin film deposition process and repair and compensate for mask defects in mask manufacturing.

3.4. Thermal Evaporation Technology

Thermal evaporation technology combines magnetron sputtering and electron beam evaporation, adjusting the gas pressure in the coating chamber at different stages, affecting the gas-phase collision process, and then controlling the particle energy. By controlling the particle energy low in the early stage and high in the later stage, the surface roughness of the film layer is better controlled. In addition, this technology is often combined with a soft X-ray reflectometer for real-time monitoring of the film thickness, with very high control accuracy for the film thickness. The extreme ultraviolet Mo/Si multilayer film prepared by this deposition technology has a reflectivity of up to 70.15% for 13.5 nm extreme ultraviolet light [10].

4. Multilayer Film Optimization Method

Diffusion between layers and interface roughness of the layers are the main factors affecting the reflectivity of multilayer films. In addition to improving the performance of the film itself, the protection and maintenance of the film are also crucial. During the operation of the lithography machine, plasma not only generates EUV photons but also tin ions and neutral debris [11]. The interaction between the debris flow and the multilayer film can cause irreversible damage to the film. At the same time, residual gases such as water and photoresist gas in the system will accumulate on the surface of the film. Regular cleaning is required to ensure performance.

4.1. Inhibition of Layer Diffusion

The high temperatures can amplify the intrinsic diffusive tendencies between the layers, and in more extreme instances, can lead to the degradation of the multilayer film’s performance. Adding diffusion barrier layers is currently an effective way to inhibit atomic diffusion in multilayer films and improve thermal stability. For extreme ultraviolet Mo/Si multilayer films, Chkhalo et al. [12] used Mo/Be as the combination material and Si as the diffusion barrier layer to prepare a more optically superior Mo/Si/Be multilayer film. Currently, the reflectivity of this multilayer film for extreme ultraviolet light at a wavelength of 13.5 nm is as high as 71.1 %.

4.2. Ensuring the Profile of the Film Surface

The thickness of the multilayer film needs to be distributed in a gradient along the radial direction according to the change of the incident angle. Currently, two methods can be used: the modification of the baffle and the modulation of the rotary table's orbital speed. The modification of the baffle is suitable for electron beam evaporation methods, by controlling the deposition path and thickness distribution of the evaporated material, achieving control over the thickness gradient. The modulation of the rotary table's orbital speed is suitable for magnetron sputtering methods, by adjusting the orbital speed of the substrate, achieving gradient control. The Lawrence Livermore Laboratory used this method for the preparation of MET multilayer films and successfully controlled the surface shape error to 0.06 nm [13].

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4.3. Pollution Prevention and Cleaning of the Film Layers

Film layer pollution mainly focuses on tin pollution, carbon pollution, and oxidation pollution.

Tin contamination comes from tin-based laser plasma light sources, where high-energy lasers irradiate tin droplets to produce EUV light, releasing tin ions and neutral particles. Researchers reduce tin debris by controlling the quality of tin target materials, introducing buffer gases, or applying external magnetic fields. Takenoshita K et al. [14] mixed 30% tin into an aqueous solution, creating tin droplets between 30 and 40 micrometers in size, and used a cold trap to capture unused target material, reducing neutral debris.

Carbon contamination is formed when hydrocarbons adsorbed on the surface of optical components dissociate under the action of photons, electrons, and ions. Currently, carbon contaminants are cleaned by hydrogenation and chemical etching, which react with carbon atoms to form volatile hydrocarbons [11].

Oxidation contamination occurs when reactive oxygen atoms react with the surface materials of multilayer films to form oxides, leading to a decrease in reflectivity. Theoretically, molybdenum/silicon multilayer mirror reflectors have higher reflectivity with molybdenum layers as the top layer, but molybdenum is unstable in air and requires an anti-oxidation material as the top layer. Tsarfati T et al. found that the combined use of atomic hydrogen and atomic oxygen can remove oxides and hydrocarbons formed on exposed ruthenium protective layers in the atmosphere [15].

5. Future Multilayer Film Technology

With the needs of semiconductor manufacturing and the development of advanced photolithography technology, BEUV lithography using a 6.X nm light source wavelength has become a research hotspot. Theoretically, the reflectivity of La-based multilayer films for BEUV in the 6.X nm band can reach over 78%. Therefore, the BEUV lithography wavelength has been set at 6.X nm.The period thickness of the multilayer films in the 6.X nm band for near-normal incidence has been reduced from 7.0 nm to about 3.4 nm, which makes the impact of the intermixing layer between La-based system multilayer film interfaces on reflectivity greater, and places higher demands on the accuracy of deposition processes, interface control technology, and equipment stability [16]. Although some foreign scholars have already prepared 6.X nm multilayer films with reflectivity exceeding 60%, there is still considerable room for improvement compared to theoretical values [17].

6. Conclusion

Extreme ultraviolet multilayer coatings are critical optical components for EUV lithography, and their commercial value and strategic significance have made them a research hotspot in the field of advanced lithography. After years of overcoming challenges, thanks to mature preparation techniques and relatively comprehensive optimization strategies, the performance of EUV multilayers has seen significant improvements in areas such as high reflectivity, peak wavelength matching, surface figure preservation, and thermal stability, providing a solid foundation for the research of EUV lithography systems. Additionally, the service life of the coatings has been extended due to advancements in contamination prevention and cleaning technologies. With the semiconductor manufacturing industry's demand for higher resolution, the next-generation 6.X nm EUV lithography technology is a research hotspot. This technology places higher demands on the performance of multilayers, particularly in terms of reflectivity, bandwidth, and thermal stability. Future research directions should focus on further optimizing the preparation process of multilayers, enhancing their optical and thermal properties, and resistance to contamination, as well as exploring new material systems to meet the needs of next-generation lithography technologies.

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