The Development of Dioptric Projection Lenses for Deep Ultraviolet Lithography

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Advanced dioptric projection lenses from Carl Zeiss are used in some of the world’s most advanced deep ultraviolet projection lithography systems. These lenses provide a resolution of better than 100 nm across the entire field of view with a level of aberration control that maximizes critical dimension uniformity and lithographic process latitude. These dioptric projection lenses are currently being used for critical layer device patterning for a wide array of complex logic, memory, and application specific integrated circuits.

Key words: lens design, dioptric lenses, monochromat, microlithography, microscopy, ultraviolet, aspheres, immersion lithography

1. Introduction

Zeiss’ involvement in the development of ultraviolet lenses goes back to the year 1902, exactly 100 years ago, when Moritz von Rohr calculated the first monochromatic ultraviolet micro-objects for ultra-high resolution microphotography using a line-narrowed source. The modern dioptric projection lenses for lithography are influenced by the collective experience in the field of microscopy, and the more recent experience with early step-and-repeat lenses. This paper discusses some of the foundations of modern dioptric designs in the context of this history, demonstrating that rapid synthesis of designs is possible using combinations of monochromatic microscope objectives and early step-and-repeat lenses from the 1970’s. The problems associated with ultra high numerical aperture (NA) objectives are discussed. Specifically, it is demonstrated that aspheres can be used effective to reduce the volume of full field projection lenses, making the mechanical implementation of a 0.90NA lens feasible in production. Several contemporary dioptric projection lens designs are reviewed in detail. The extension of these designs to numerical apertures greater than 1.0 using immersion techniques is demonstrated. These immersion lenses give the potential for 40 nm resolution.

The manufacture of integrated circuits with smaller and smaller features demands leading-edge projection lenses with specifications which no one would have considered possible a few years ago. The Rayleigh resolution (R) of a lithographic printing system is expressed as:

\[ R = k_1 \lambda / NA \]  

where \( k_1 \) is a process dependent factor, \( \lambda \) is the wavelength of illumination, and \( NA \) is the numerical aperture. The process dependent \( k_1 \) factor takes into account several factors such as partial coherence and the influence of the resolution enhancement techniques such as off-axis illumination and phase shift masks. Wavelength scaling, numerical aperture scaling, and \( k_1 \) process optimization have all been used to improve resolution. For example, a projection lens with a numerical aperture of 0.70 operating at 193 nm can achieve a resolution of 100 nm in resist, assuming a \( k_1 \)-factor of 0.36.

Sematech’s International Technology Roadmap for Semiconductors (ITRS) shows that leading edge 130 nm design rules are achieved today using either 248 nm or 193 nm technology. These high numerical aperture tools are almost exclusively supported by dioptric projection lens technology in a step and scan mode. The ITRS predicts that 100 nm design rules can be achieved in production using 193 nm lithography, meaning that proven dioptric lens technology will likely be the technology of choice at this next device node at the critical layer. But even as the industry eventually moves to adopt new technologies at the critical layer (e.g., 157 nm and extreme ultraviolet) to gain even higher resolution and smaller design rules, the demands on imaging at the sub-critical layers also increases. So the critical layer scanners of today will become the sub-critical layer scanners of tomorrow. Effectively this means that dioptric projection lenses will continue to be the work horse for lithography for many years to come.

As a company, Carl Zeiss has been involved in the development of deep ultraviolet (DUV) imaging systems for over 100 years. The roots of this fundamental work in deep ultraviolet microscopy are often seen in today’s dioptric projection lenses with little imagination. Line narrowing was used then and is used now to overcome problems with dispersion and lack of suitable materials in the deep ultraviolet. The imaging group closest to the wafer in a modern dioptric lens for lithography often resembles a monochromatic ultraviolet objective for microscopy with several aplanatic or near-aplanatic surfaces in the final focusing group. The groups between the reticle and the aperture stop often have a series of bulges and waists, reminiscent of the lenses described by Glatzel over 20 years ago.

The development of modern dioptric projection lenses for deep ultraviolet lithography can be seen as an extension of this collective work. In the following sections, we discuss the historical foundation of our deep ultraviolet lens work from the early 1900s starting with monochromatic high numerical aperture microscope objectives until the early 1980s with early ultraviolet repeater lenses. We demonstrate how one skilled in the art is able to synthesize a high numerical aperture dioptric lens by combining these different design forms as a starting point for further optimizations.

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Since the potential of dioptric projection lenses has not yet been fully exploited, we discuss the progress with hyper numerical aperture designs with numerical apertures to 0.90. A monochromatic design example is provided for use with a highly line-narrowed laser (0.25 pm). It is shown that the system can be designed to approach the "zero aberration" condition as required by modern lithographic process to minimize linewidth variation across the imaging field. Dioptric projection lens can also utilize a second material, thus forming "pseudo doublets" to improve the state of color correction at the expense of lens complexity. Design examples using this construction are also presented.

Finally, we provide the motivation to once again borrow from our past and explore the field of immersion lithography. Immersion imaging has already been fully established in microscopy for more than 100 years. The resolution gain offered by immersion could allow the lithographic industry to continue to satisfy Moore's law, which states that the performance of leading-edge integrated circuits doubles every 18 months with decreasing manufacturing cost. We provide two examples of immersion lenses for both 193 nm and 157 nm lithography designed so that a numerical aperture value of 1.1 is obtained. These lenses are capable of resolutions of 50 nm and 40 nm, respectively, suggesting that immersion could be used with even larger numerical apertures to achieve linewidths to 30 nm using just basis dioptric projection lenses that are already well understood.

2. History of UltraViolet Lens Development at Carl Zeiss

From the Rayleigh resolution formula, we know that the limiting resolving power of optical systems depends linearly on the wavelength. So improvements to resolution are enabled by wavelength reduction. Ernst Abbe had already recognized this and recommended the use of UV radiation for microscopic projection as early as 1874. However, the only two materials with good permeability, fluor spar and mountain crystal could not be used originally for constructing a microscope objective because of the double refraction of the mountain crystal. Only in 1899 after M. Herschko-witsch succeeded in manufacturing amorphous quartz which was sufficiently homogeneous and tension-free for optical purposes and August Köhler at the same time made clear progress in the development of a spectrally narrowed ultraviolet light, did the first UV microscope become a real possibility.

August Köhler replaced the previously common light sources with a continuous spectrum by light sources with a linear spectrum. The discharge spark of a Leydenener bottle jumping between metal electrodes proved particularly suitable. With mountain crystal prisms he isolated the single lines and got a series of monochromatic images of the spark. He projected these into the entrance pupil of the objective. He used a fluorescent image converter as a receiver. August Köhler worked at first with the magnesium line at 280 nm, a little later with the sharper cadmium line at 275 nm. The Figs. 1 and 2 show the UV-spectral apparatus and a principle diagram of the used monochromator. The refractive index of fluor spar and quartz are so close together that the achromatic structure which has since been used for large numeric apertures failed in 1900.

In the Spring of 1902 the Zeiss scientist Moritz von Rohr discovered a totally new type of lens which, with a suitable lens combination was asplanatic for any certain wavelength to be chosen within limits. In these lenses the refractions were distributed evenly onto the individual surfaces by following them with a series of aplanar meniscuses of diminishing strength. To improve the aplanatism, Moritz von Rohr has additionally used a dispersive meniscus as a means of correction. The first three monochromates of melted quartz for 280 nm and 275 nm resulted. 1930s a new series of monochromates was developed for 257 nm. Further calculations were made at Carl Zeiss at the end of the 1950s. The Fig. 3 shows selected design examples from the variety of these UV monochromates.

The use of radiation sources with a continuous spectrum in combination with monochromators and a spectral bandwidth of approx. 5 nm led to the development of achromatic UV-VIS lenses of quartz and CaF$_2$—one even with additional LiF—, which Carl Zeiss has been offering as