The Development of Dioptric Projection Lenses for DUV Lithography

Willi Ulrich, Hans-Jürgen Rostalski, Russ Hudyma*
CZ SMT AG, D-73446 Oberkochen, Germany
*Paragon Optics, Inc., San Ramon, CA

ABSTRACT

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.

Zeiss' involvement in the develop of ultraviolet lenses goes back to the year 1902, exactly 100 years ago, when Moritz von Rohr calculated the first monochromatic ultraviolet micro-objectives 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 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 0.90 NA 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 40nm resolution.

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

1. INTRODUCTION

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 resolution (R) of a lithographic printing system is expressed as:

$$R = k_1\lambda/NA \qquad (1)$$

where k_1 is a process dependent factor, λ 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 like 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 k1-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. 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 satisfiy 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, fluorspar and mountain crystal could not be used originally for constructing a microscope objective because of the double refraction of the mountain crystal[1]. Only in 1899 after M.Herschkowitsch[2] 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[3,4] replaced the previously common light sources with a continuous spectrum by light sources with a linear spectrum. The discharge spark of a Leydener 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 280nm, a little later with the sharper cadmium line at 275nm. The figures 1 and 2 show the UV-spectral apparatus and a principle diagram of the used monochromator. The refractive index of fluorspar 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[5] discovered a totally new type of lens which, with a suitable lens combination was aplanar 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[6,7]. The first three monochromates of melted quartz for 280nm and 275nm resulted.

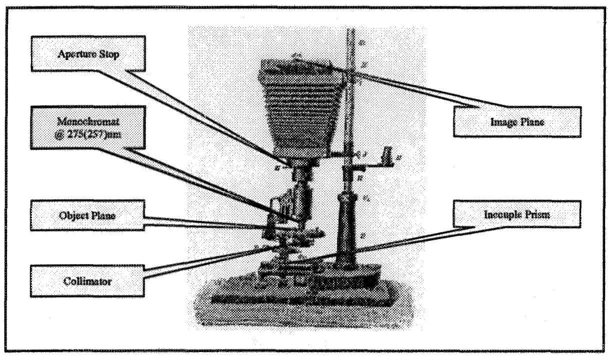

Fig. 1: UV-spectral apparatus developed by August Köhler in 1904

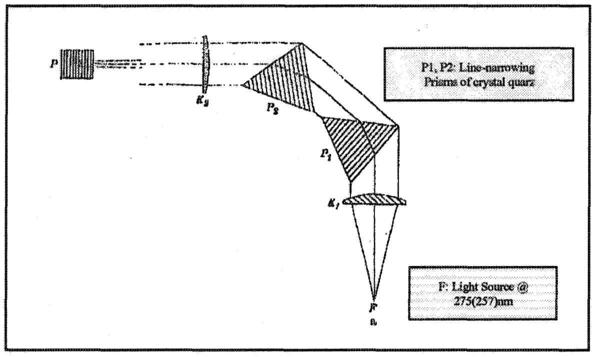

Fig. 2: Line-narrowed source for UV-Microphotography

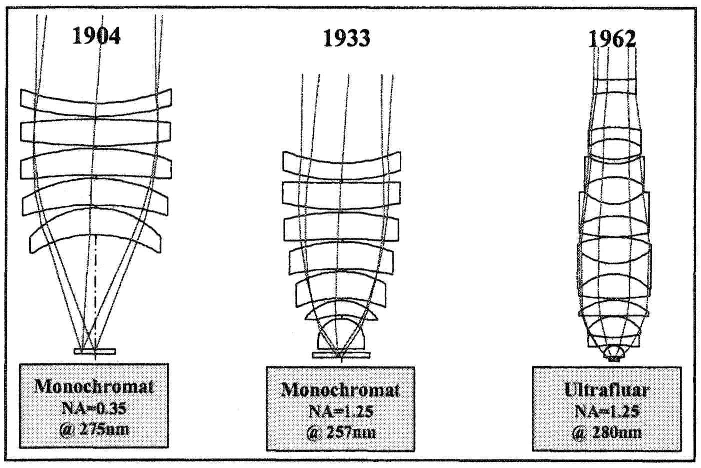

Fig. 3: Carl Zeiss UV-Microscope Objectives

In the 1930s a new series of monochromates was developed for 257nm[8]. Further calculations were made at Carl Zeiss at the end of the 1950s. The figure 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. 5nm 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 ultrafluars since the 1960s[9,10].

The development of ultraviolet lenses at Carl Zeiss found a different path starting in the late 1960s. Ultraviolet reduction lenses intended for the production of masks and later for direction projection onto a wafer were developed at the g-line, h-line, and later i-line. These lenses were derived from photographic objectives and allowed to grow in size to become as relaxed as possible. These lenses required very tight control of distortion. Compared to microscope objectives, these lenses were perhaps the first multi-element lenses requiring diffraction-limited performance with a very tight control of distortion across a large field[11]. Since the correction of the large image field proved to be particularly difficult, Erhard Glatzel of Carl Zeiss recommended designs of the distagon type, a combination of retrofocus lens and double Gauss lens in the rear group[12]. Due to the non-availability of high-index materials, he proposed the correction means of multiple “bulges”[13] according to the recommendation of H.Slevogt[14] in order to reduce field curvature. Figure 4 shows a selection of the first Carl Zeiss repeater lenses from the 70s. The double "bulging" of the lenses can be seen here very nicely. Gerhard Ittner[15] of Carl Zeiss shows in an example of a further design development of the S-Planar 1.6/50 how the number of lenses has to be increased at an aperture increase from 0.28NA to 0.40NA.

In 1980 Phillips and Buzawa described new high-resolution lenses for 365nm lithography[16]. They, as well as Glatzel and Braat[17], recommended avoiding balancing large high order aberrations because this usually introduces zonal imbalances. The proposed correction means like further splitting of positive lens elements, adding a thick meniscus element near the image and adding an aspheric at the stop were well known and used in different recent optical systems like microscope objectives and camera lenses.

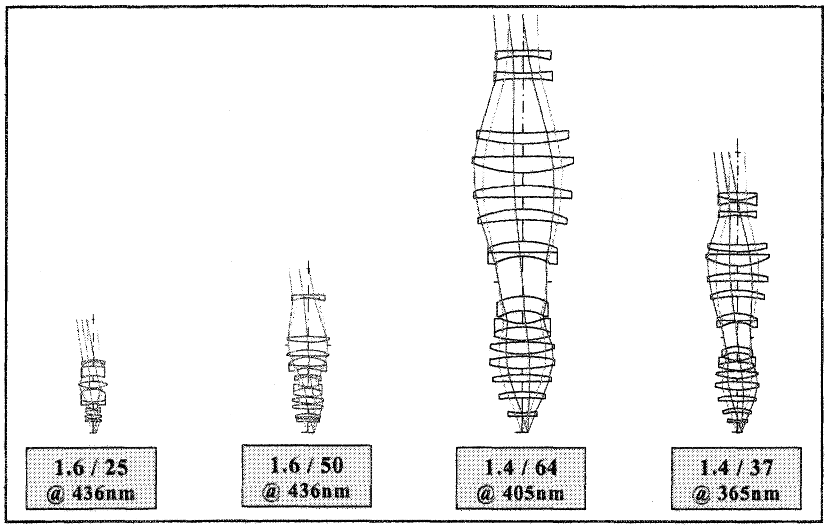

Fig. 4: A selection of the first Carl Zeiss repeater lenses from the 70s

All later all-refractive lens designs go back to the concepts of Erhard Glatzel. In 1987, Joseph Braat demonstrated on an 18-lens 0.38NA design example from Cerco how the double bulging proposed by Glatzel could be logically developed. An additional first positive lens group simplifies the correction of the Petzval sum and at the same time enables the demand for telecentering on both sides to be met[18]. Carl Zeiss Jena already used this lens structure in 1979 to design the double-sided telecentric projection lens UM-AÜR with a numerical aperture of 0.4NA[19].

This history can be drawn upon as we consider the development of new lens forms that satisfy more contemporary lithographic requirements. Combining scaled versions of some of these traditional design forms enables synthesis of "new" starting points that contain the waists and bulges as decribed by Glatzel, as well as the aplanatic constructions contained in the early monochromatic microscope objectives. Figure 5 illustrates a fairly relaxed example that was created via the combination of an early photorepeater (S-Planar 50 mm, f/1.6) and a monochromatic microscope objective first calculated in the 1930s. The photorepeater objective is turned around since its image space numerical aperture is compatiable with the required numerical aperture at the mask. After this flip, each part of the lens is scaled to give the desired reduction from mask to wafer of 4x. The cemented doublets in front of the stop are split and the bendings of the G5 group are readjusted somewhat to accounts for conjugates shifts. This lens has one strong waist and one weak waist near the stop. With material changes and direction from one skilled in the art, this starting point could be made to take either the one-waist (two bulges) or two-waist (three bulges) form.

Taking a Maxwellian view, if an observer stands at the aperture stop and peers toward the wafer, he sees a lens that looks like the early microscope objective. Looking the other way, the observer sees the photo-repeater. With a little imagination, many contemporary dioptric projection lenses for either KrF or ArF lithography can be thought of in this manner. What makes these designs work is the fact that you have positive and negative lens groups working together to balance the different aberrations using their respective undercorrected and overcorrected components.

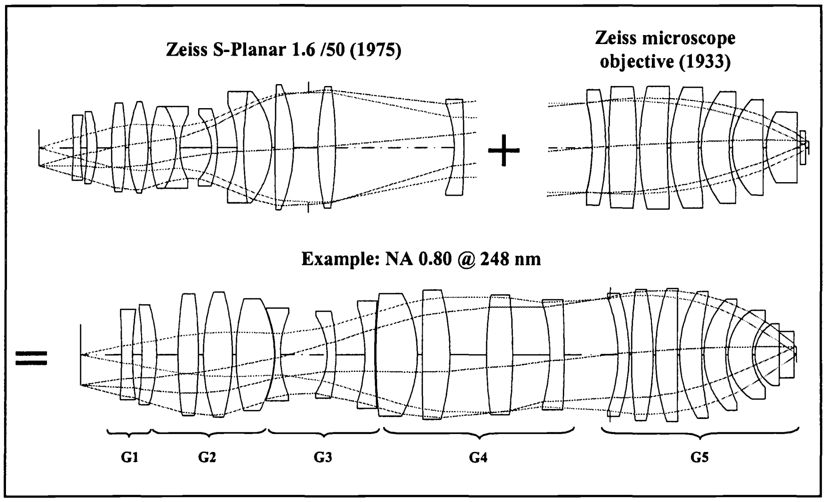

Fig. 5: Rapid synthesis of designs is possible by simply combining scaled versions of traditional lens forms. Here an early photo-repeater is flipped, scaled, and combined with a scaled monochromatic objective from the 1930s.

3. COMPACT HIGH-NA LENSES

At the SPIE 2000[20] it was demonstrated how new refractive designs of a compact form could be produced for DUV microlithography by using aspheres[21]. The lens volume could be significantly reduced in comparison with earlier, purely spherical versions[22]. By further progress in design over the last two years, optical designs with a numeric aperture of 0.9NA[23] and greater have been achieved whose lens volumes are even below the extrapolation curve forecast two years ago (Figure 6).

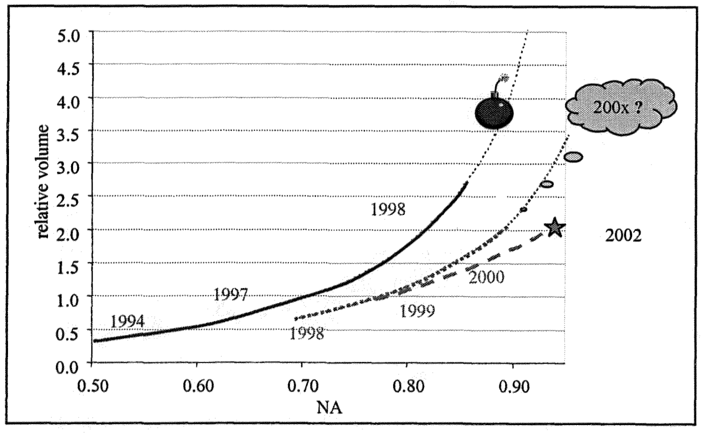

Fig. 6: Lens volume as a function of numerical aperture. Compact high- and hyper-NA lenses become feasible through the use of aspheres.
Upper line: spherical designs
Lower lines: aspherical designs

These material saving refractive designs are distinguished by a suitable compromise between number of lenses and number of aspheres used. The first bulge has shrunk in comparison with the earlier 0.8NA design and does not really exists at all any more, the central waistline exhibits an even greater constriction than previously. With this design concept, the tracklength only had to be increased by 10% and the maximum diameters in the stop range were increased by less than the percentage aperture increase (Figure 7). These design means also improve the limiting chromatic longitudinal error.

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