Requirements and designs of illuminators for microlithography

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ABSTRACT

The beam shaping by illuminators of microlithographic optical systems is a key technological contributor to the advancement of mass production of integrated circuits. The following examines both the requirements and the design of these illumination systems. The importance of partial coherence, off-axis illumination, polarization, telecentricity and uniformity for the lithographic process are discussed. The design sections cover the systems from source to reticle, including the use of diffusers, axicons, kaleidoscopes and fly's eyes arrays.

Keywords: illuminator, microlithography, off-axis illumination, uniformity, telecentricity, partial coherence, fly's eye array, kaleidoscope, axicons, diffusers

1. INTRODUCTION

The ability to transfer a tremendous amount of information in a fraction of a second from reticle to silicon wafer through reduction imaging has made microlithography a premier element to the success of mass fabrication of integrated circuits.

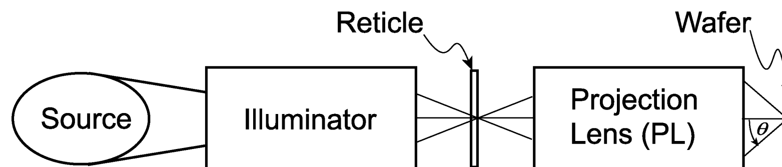

Figure 1 – Simplified microlithographic system from source to silicon wafer

The projection lens images at typically 1/4x, with wavefront deformations on an order of 1/50th of the wavelength and image placement accuracies on the nanometer level over centimeter image fields. This is accomplished with lenses that contain 20 to 35 optical elements. The illuminator does not require as tight a fabrication precision as the projection lens, but does have demanding requirements that challenge the designer. The illuminator not only produces uniform irradiance over the imaging field, but also "sculpts" the diffraction pattern in the pupil that forms the image at the wafer.

2. MICROLITHOGRAPHY ESSENTIALS

A lithographic tool needs to maintain the critical dimensions (CD) of the printed features within 10% variation typically over the field. One key parameter to CD control is the exposure energy, which will vary the dimension size. A second key parameter is the depth of focus (DOF) at the wafer. The exposure energy and DOF define the process window for printing acceptable features on the wafer. The CD and DOF are defined to these key parameters by the equations,

$$CD = k_1 \frac{\lambda}{NA_{PL}} \quad \textbf{(1)} \qquad DOF = k_2 \frac{\lambda}{NA_{PL}^2} \quad \textbf{(2)} \qquad NA_{PL} = n \sin\theta \quad \textbf{(3)}$$

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where the projection lens' numerical aperture (NA_{PL}) is a function of the imaging medium index (n) and the imaging cone angel (θ). The drive to faster chips via smaller features has historically had more push on wavelength than numerical aperture, since lowering the wavelength has less deterrence on the DOF. The mass production of integrated circuits has moved from the Hg lamp g-line (436nm) in the 1980's, through i-line (365nm), to the KrF excimer laser (248nm), the ArF excimer (193nm), to F_2 excimer (157nm) and back to 193nm. Nitrogen purging allows 157nm imaging avoid the use of vacuum. Yet, there are still difficulties with materials and other concerns that have stalled development.[1] The next step in wavelength is expected to be to the extreme ultraviolet (EUV) near 14nm. This is a wavelength region in which thin film coatings can be fabricated for these all-reflective designs. Before the step to EUV, the push to smaller features by numerical aperture is in the forefront by changing the imaging medium index. The immersion medium of choice for 193nm has proven to be water. Along with NA and wavelength, gains have been made in the resolution factor k_1 and the depth-of-focus factor k_2. These factors have been improved by many process techniques, and the influence of illuminators on these values in particular will follow in the next section.

As microlithography has progressed, the number of features, or the bandwidth product, has reach values on the order of 10^{11} to 10^{12} per exposure.[2] The illuminator not only modifies the uniformity of the exposure over the field, but also the placement of these features in the image. The telecentricity of the illumination, which is described in detail in the next section, can alter the magnification and distortion of the imaging field. The precision of feature positions is essential for the overlay of tens of layers on a chip to the nanometer scale.

3. THE ILLUMINATOR'S INFLUENCE ON LITHOGRAPHY

3.1. Partial Coherence

The ratio σ of the illuminator's NA and the projection lens' NA,

$$\sigma = {NA_{Illum}}/{NA_{PL}} \quad \textbf{(4)}$$

is defined as a value of partial coherence. The illuminator's aperture stop is imaged at the projection lens' aperture stop, and since NA maps linearly to pupil dimensions for a well-corrected system, the relative sizes of these stops is also the value σ.

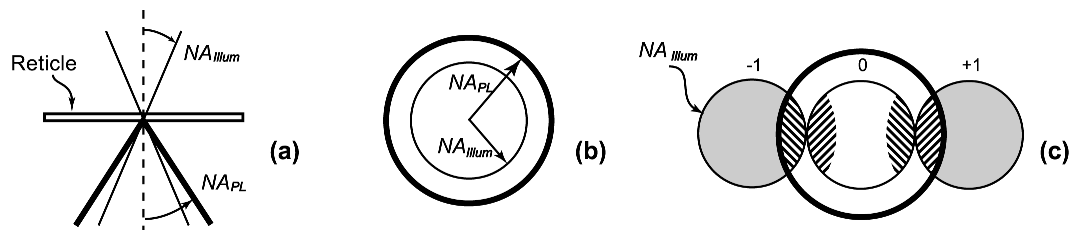

Figure 2 –Depicting partial coherence (a) at the reticle and (b) at the projection lens' aperture stop. (c) is a representation of the distributions at the aperture stop for imaging a diffraction grating. The grey areas represent light blocked by the projection lens' aperture stop, while the hatched regions represent area of the pupil interfering in the image formation. The numbers –1,0,+1 refer to diffraction orders in (c).

The value of σ only describes the perimeter of the image of the illuminator's aperture stop. The irradiance distribution of the whole illuminator's stop or pupil has influence on the imaging and is referred to as the "effective source" in partial coherence theory.[3,4] The results of an aerial image calculation shown in Figure 3 reveal that there is an optimum σ for depth of focus, though not the same for peak contrast on axis. The term 'aerial' indicates that the image was simulated in air and that the influence of the resist was not taken into account. This calculation, a 193nm system at a NA of 0.75, also has a flat top distribution as an effective source, meaning the irradiance at the pupil or aperture stop is uniform.

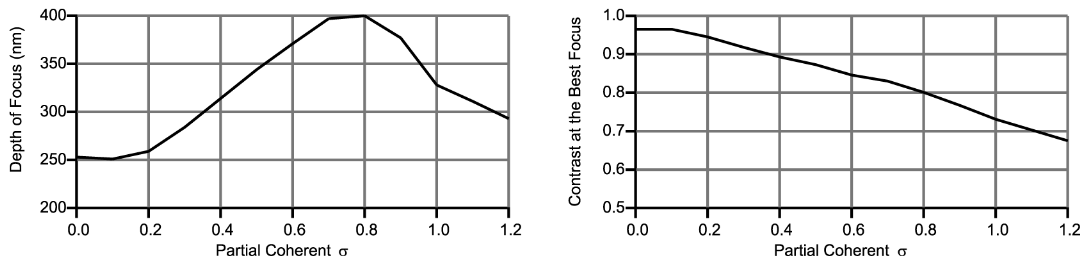

Figure 3 – An aerial image analysis demonstrating the variation of depth of focus and contrast versus partial coherence.

If the distribution of the effective source is Gaussian, the results are different. The illuminator needs to maintain the effective source size and distribution over the whole imaging field, or the process window will be diminished. More recent illuminators have adjustable partial coherence for optimizing the printing of specific masks. The calculation shown in Figure 3 was for an amplitude mask or reticle, such as chrome on glass. In the case of imaging phase-shifting masks, the optimum partial coherence σ is very low, which places further demands on the illuminator for efficiency, uniformity and telecentricity.

3.2. Off-Axis Illumination

In the early 1990's, the techniques of using off-axis illumination known in microscopy for some time were introduced into microlithography.[5,6,7,8] In the case illustrated in Figure 4, in which the 0 order and +1 diffracted order have the same magnitude of angle of incidence at the wafer, then the optical path along the 0 and +1 order are equal for both planes in and out of focus, and thus the depth of focus is expanded.

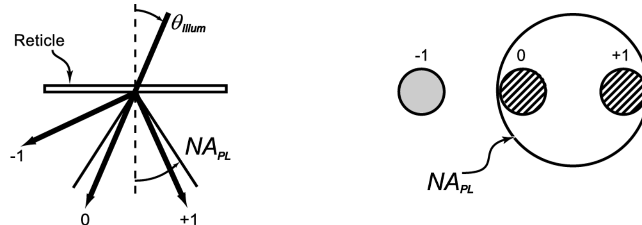

Figure 4 – The diffracted orders of off-axis illumination at the reticle and at the pupil (aperture stop) of the projection lens. The –1 order in grey is blocked by the aperture stop, and the 0 and +1 orders interfere to form an image.

To counter that the 0 order has more energy than the +1 order, a second off-axis point opposite the first is used. This is the dipole illumination condition, which is optimum for dense features in one direction.[9] The use of quadrupoles improves the DOF for dense features in two directions and an annular stop improves them at any orientation.

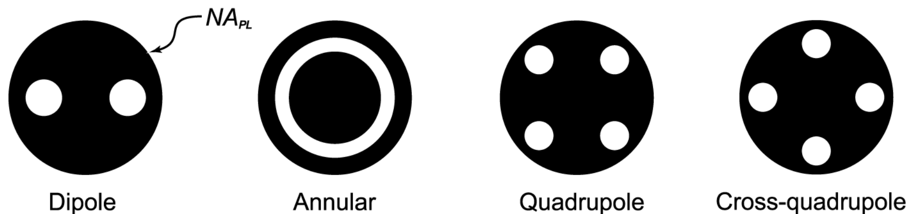

Figure 5 – Some common off-axis illuminator pupil fills or effective sources.

Once again, the illuminators need to be adjustable to these different illumination pupil distributions, while still meeting all other requirements, such as uniformity and telecentricity. Why this is difficult when the pupil is largely

filtered in the case of off-axis pupil profiles and the low σ for phase-shift masks will be discussed in the design section.

3.3. Telecentricity

All lithographic projection lenses are designed to be telecentric at the wafer, in order to maintain the same magnification through the DOF. An imaging lens is considered telecentric, if a ray that emits from the edge of the field and passes through the center of the aperture stop is normal at the image plane. Though this simple definition is useful, it is the angle of incidence of the energy centroid of the illumination angular distribution at the wafer that ultimately defines where a feature will move with defocus.

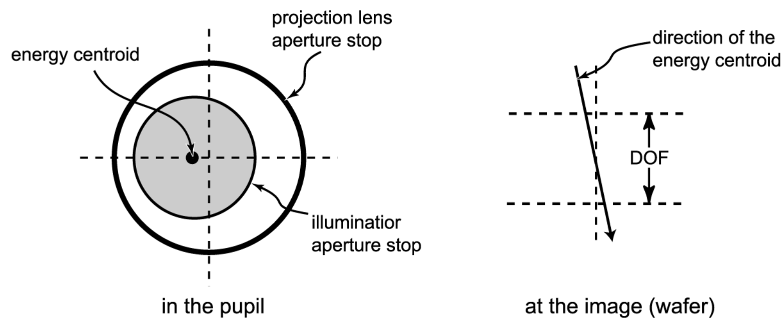

Figure 5 – The representation of an energy centroid at the aperture stop of the projection lens and at the wafer.

In other words, it is the illuminators' pupil distribution that determines the telecentricity of the system. The terms 'telecentricity' and 'uniformity' describe a condition, but the terms are also used to describe the value of deviation from these idea conditions. Typically the requirement, or telecentricity specification, allows a shift on the nanometer scale over the DOF, which equates to a few milli-radians from normal incidence.

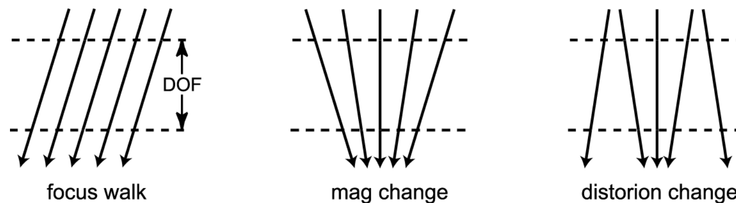

Figure 6 – Telecentricity changes over the imaging field has different results on the lithography with exposusres through focus.

If the telecentricity is out of specification, then the alignment of features from one lithographic layer to the next of an integrated circuit will fail with variations in focus during exposures.

3.4. Uniformity & Dose Duration

Both the duration of the exposure and the irradiance distribution over the imaging field influence the variation of the intended critical dimensions (CD) due to dose over the field. The much more difficult to control of the two is the irradiance distribution that needs to account for the transmission of tens of optics from the uniformizer to the wafer. The specified uniformity or accumulated irradiance of a dose at the wafer is typically near +/-1% for all illumination conditions. This is measured and specified for non-imaging conditions, since overfill of the aperture stop can modify the results.

3.5. Polarization

Two polarized propagating waves cannot interfere if their electric field (E) vectors are perpendicular to each other. Consider imaging a grating, the ability of transverse magnetic (TM) or P polarized light of two diffracted orders to interfere will diminish as they approach 45º incidences in the resist, while transverse electric (TE) or S polarized light will interfere at all angles of incidence. These two polarization conditions are shown graphically in Figure 7, along with a vector diagram of an azimuthally polarized electric field in the illumination aperture that would allow interference for any orientation of dense lines being imaged.

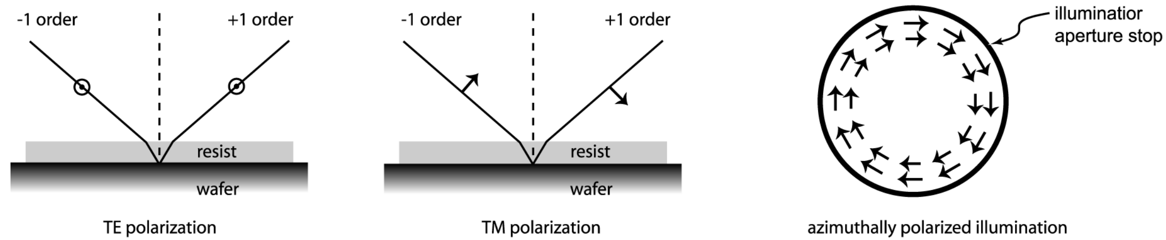

Figure 7 – The electric field vector is pointing out of the page for the two beams polarized TE and forming an image in the resist. If the pupil of the illuminator is polarized azimuthally, then TE is obtained for all orientations of the first orders.

The importance of polarization is more evident with immersion lithography, due to the higher angles of interference obtained in the resist.[10,11] Immersion also reduces the index change at the resist, which improves the coupling of the electric fields into the resist as calculated by the Fresnel equations of reflectivity. If light does not interfere at the image, then it is background or stray light that lowers the contrast of the image. Polarized light not only improves upon this situation, but also optimum pupil distributions that have greater efficiencies of interference.

4. ILLUMINATOR DESIGN

4.1. Illuminator Layouts

The previous section discusses how the illuminator can influence the lithography through shaping the spatial and angular energy distributions at the wafer. The projection lens has little influence on these distributions due to the high degree of aberration correction, with the possible exception of transmission variations across the pupil due to the performance of thin film coatings. This section discusses some of the illuminator design issues and solutions.

The illuminator, from source to reticle, can be divided into three sections as shown in Figure 8. The rays in this diagram are traced backward from the reticle to the source. The mixing of the rays in the kaleidoscope is evident by their scrambled manner near the source.

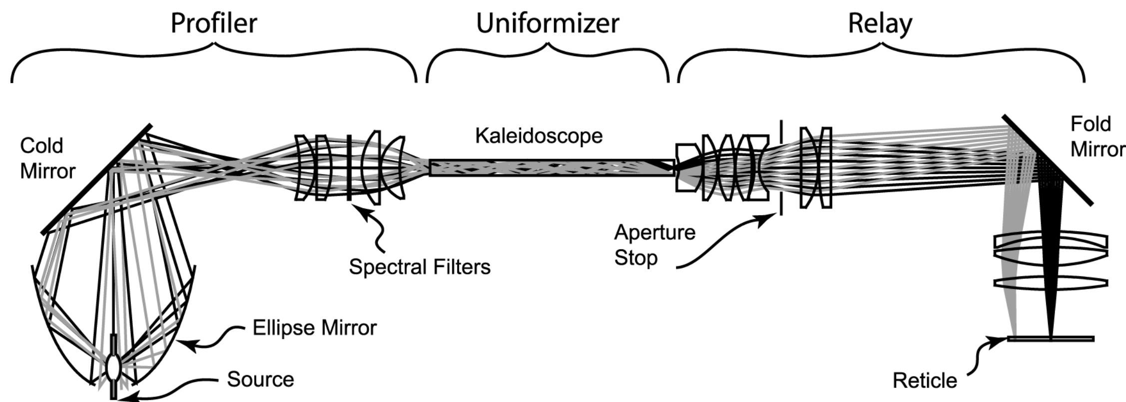

Figure 8 – A simple lamp illuminator broken down in to three generalized sections.

The “profiler” can also be called a “beam shaper, ” since this section collects and forms the energy from the source to the desired distributions at the uniformizer. The “uniformizer,” as named, produces a uniform field. In the case illustrated, this uniform field is found at the end of the kaleidoscope. The “relay” images this plane and controls the telecentricity and the final shaping of the pupil distribution across the imaging field.

4.2. Sources & Profilers

Mercury (Hg) lamps and excimer lasers have been the two main sources used in microlithography for decades. The path of cutting edge lithography has gone from g-line (436nm), or combination of g & h (405nm) lines, to i-line (365nm) sometime in the late 80’s, but are still being sold today for less demanding lithography. These lamps are typically in the 1 to 5kW range and generate a great deal of infrared radiation that is easier to removed with filters in reflection (cold mirrors) as opposed to transmission. Except for catadioptic designs, the rest of the lamp’s spectrum needs to be narrowed to a bandwidth of a few nanometers by additional filtering. Lamp systems also need to be shuttered for controlling the duration of the dose. If the narrowband filter and shutter are placed in the profiler section, the uniformizer will also uniformize their actions over the imaging field.

Lasers, as opposed to lamps, fill much less of an optical invariant, the product of the spatial and angular energy distribution ranges. In the case of the source, the optical invariant can be described as the volume into which light is emitted. At the wafer plane, the optical invariant is the product of the area of the imaging field and the square of the illuminator’s NA. One of the design intents for a lamp profiler is to optimize the fill of this invariant to increase the irradiance at the wafer. A lamp source has a much larger invariant than the wafer and the profiling optics are design to collect the brightest portions of this volume. Higher irradiance at the wafer shortens dose durations and thus increases the wafers per hour that can be printed. It is common practice to collect the light from the lamp with an elliptical or nearly elliptical reflector. The lamp is at one of the foci and blocks a central portion of the angular extent of the image at the other. This produces a “hole” or dark region in the invariant volume. One means to fill this hole partially is to use an optic with a cone-shaped optical surface known as an axicon.

The other design intent for the profiler section is to shape or profile the energy entering the uniformizer. It is these energy distributions that shape the enveloping distribution at the at the aperture stop of the illuminator. If an annular stop is used, as shown in Figure 5, much of the light will be blocked unless the profiling section can create an annular fill. This fill can be achieved with axicons, as shown in Figure 9.[12] The separation of the axicons can alter the diameter of the annular fill at the stop, or remove it completely by closing the separation. In order to fill the hole made by a lamp, the axicons are flipped left to right as shown in Figure 9.

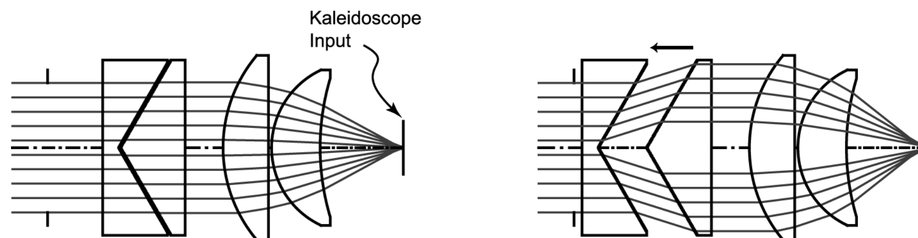

Figure 9 – Axicons can be used to create an annular fill at the illuminator aperture stop by separating the two optics.

In the case of a laser, the source fills a much smaller invariant and the profiler is designed to increase the filled invariant. If the filled invariant is not increased, the uniformizer will generate an array of points at the illuminator’s aperture stop that does cover a larger invariant. This array of points is undesirable, since it can produce both an interference pattern at the wafer and a high fluence on the optics. Uniformizers increase the invariant by dividing the incident beam into multiple beams with dark regions in between. A refractive diffuser, made by etching ground glass, can also accomplish this division. This type of a diffuser is actually a lens array of random positions, apertures and focal lengths. As expected by the central limit theorem, the resultant far field pattern is a Gaussian.[13] Each micro-lens increases the incident angular distribution of light, which increases the invariant by forming a focus of a section of the beam. This array of foci randomly distributed over the spatial extent of the incident beam forms dark

regions similar to a uniformizer. Optics that create dark regions increase the filled invariant of the light incident upon them. Figure 10 demonstrates, with a simplified profiler, a method of adjusting the invariant filled. As the diffuser is slid through the focusing laser beam, the spatial fill of the diffuser decreases, which lowers the invariant filled and the NA of the light entering the kaleidoscope.[14]

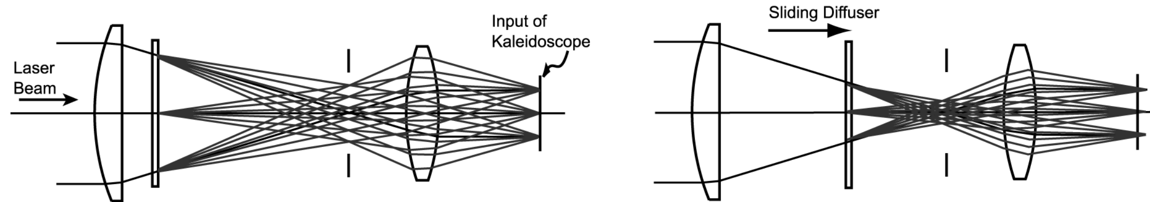

Figure 10 – Altering the NA entering the kaleidoscope by sliding a diffuser in a converging beam.

Another category of diffusers are those made by lithographic techniques. These have the advantage of being "engineered" or designed to produce a desired far field pattern, such as an annular or quadrupole pattern. An efficient means of adjusting the energy distribution at the aperture stop of the illuminator is to switch different engineered diffusers into the optical train. The diffractive diffusers produce many orders that are smoothed by the convolution of the incident illumination on the diffuser. One difficulty of using diffractive diffusers is leakage into the zero order.[15,16] There are also engineered refractive diffusers that use micro-prisms or micro-lenses to produce the desired far field pattern.[17,18]

4.3. Uniformizers & Relays

There are other methods to produce a uniform plane, but kaleidoscopes and fly's eye arrays have been the mainstay for microlithography. They both divide the beam or incident energy distributions into a multitude of sources in the aperture stop of the illuminator. The reticle and wafer are in the opposite conjugate, or Fourier transform space, of the aperture stop. Thus each source illuminates the whole imaging field and every point in the imaging field is illuminated by each source. The summation of all distributions of all the sources produces the uniform field of irradiance, which is why uniformizers are also known as integrators.

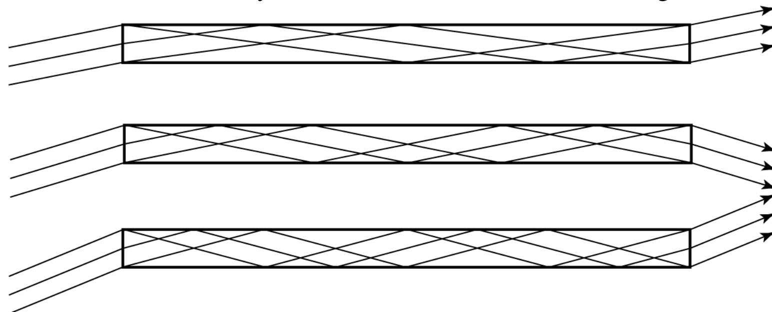

Figure 11 – The kaleidoscopes divides the incident angular distribution by reflections as shown by 2, 3 & 4 reflections.

A kaleidoscope creates multiple sources by reflections as illustrated in Figure 11. A kaleidoscope can be a rod or a tunnel. A rod is a solid that uses total internal reflection (T.I.R.) to reflect, while a tunnel is hollow and uses reflective coatings. The angular energy distribution incident on the tunnel is divided to produce a "kaleidoscope pattern" within the aperture stop, as shown in Figure 12.

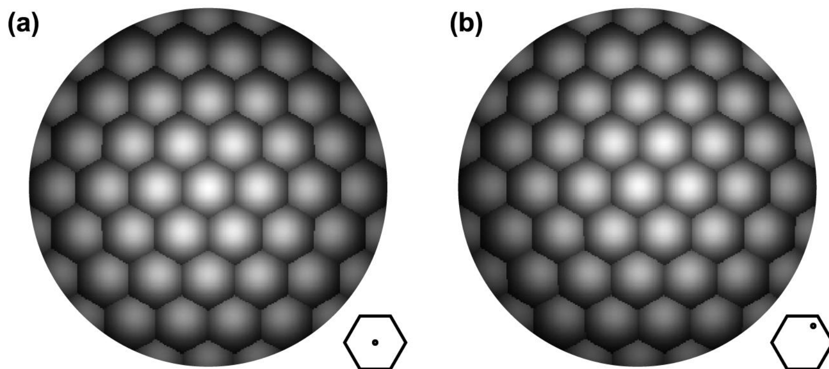

Figure 12 – The spatial distribution produced by a hexagonal kaleidoscope at the aperture stop for (a) on-axis and (b) off-axis field points. The centroid of the distribution shifts within the aperture stop with field point position. The spatial and angular distribution incident on the kaleidoscope is Gaussian for this simulation.

A hexagonal kaleidoscope, instead of a rectangular one, might be used to reduce overfill of the uniform distribution to the circular field that is available for a rotationally symmetric projection lens. Each of the overfills at the wafer, the reticle, the illuminator aperture stop and the input of the kaleidoscope reduces the transmission and the optical invariant of filled illumination and thus the optical invariant at the input of the kaleidoscope needs to be higher than at the wafer.

The importance of the centroid shift with field position, demonstrated in Figure 12, is that if the illuminator's aperture stop is imaged without defocus to the stop of the projection lens, then the centroid shift produces a non-telecentric image at the wafer. The patterns shown were generated for a system that has the input face of the kaleidoscope imaged to the aperture stop of the relay. In other words, the entrance pupil of the relay section is at the input of the tunnel.

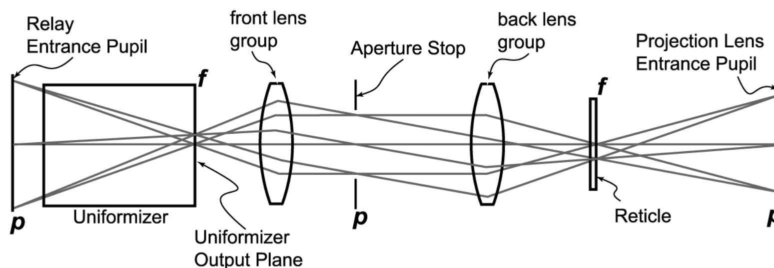

Figure 13 – A uniformizer and relay diagram, where the conjugate planes of the pupil (p) and field (f) are denoted.

If the entrance pupil is at infinity, then the centroid does not shift within the pupil, but the kaleidoscope pattern does, which has more influence on the uniformity performance. The degree of the uniformity and telecentricity are not only dependent on the entrance pupil location and geometries of the kaleidoscope, but also the energy distributions at the input of the tunnel and the aperture stop that is being used. When off-axis techniques or low partial coherence σ for phase shift masks are employed, the number of reflections available for uniformizing and for balancing telecentricity are reduced. This has driven the designs to use uniformizers that create more sources or divisions. In the case of a kaleidoscope, this requires increasing the ratio of length and face width to increase the number of reflections.

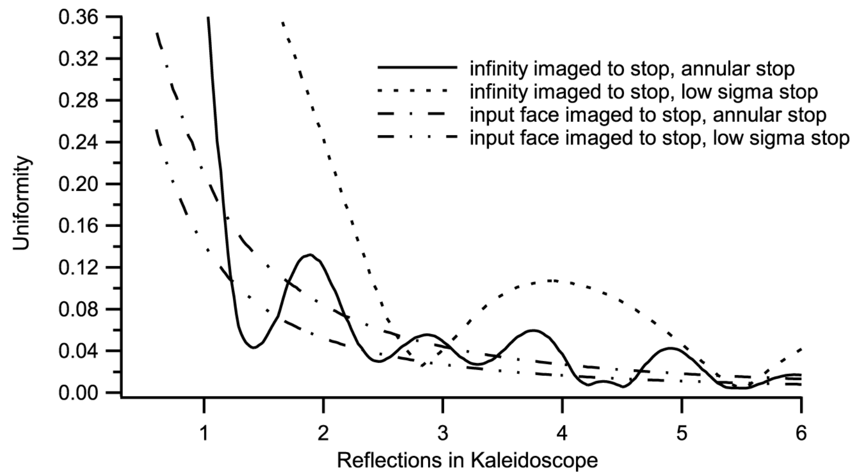

Figure 14 – The results of a calculation emphasizing the dependence of uniformity on the number reflections for two different aperture stops and two different positions of the relay's entrance pupil position.

A fly's eye segments the incident spatial distribution, as opposed to the kaleidoscope that segments the angular distribution. The fly's eye lens array can be, and often is, split into two separate arrays.[19] In either configuration, the "lenslets" of the first array or the first surface focuses onto the second. The second is the pupil of an imaging system that images the input faces of the lenslets to the uniform plane. The field lens is the back half of the imaging system which overlays all the images to form a uniform plane.

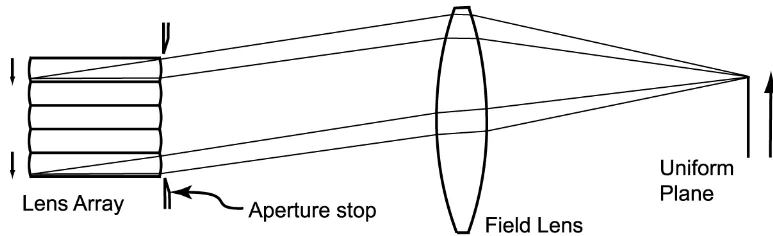

Figure 15 – The general layout of a fly's eye uniformizer. The lens array can be split into two arrays.

In order to get more sources, more lenslets are needed. One method to reduce the number of optical surfaces is to cross two lenticular arrays (stacked cylinder lenses) to approximate a spherical lens array. The field lens can be the relay portion of the illuminator, or a relay lens can image the uniform plane to the reticle. One of the advantages of the latter is that field blades can be placed at the intermediate uniform plane to limit the field that is being illuminated. The fly's eye design has the same issue with the centroid shift with field position as does the kaleidoscope.

As already implied, if the relay's lens aperture stop of the illuminator is defocused from the projection lens apertures stop, it can counter the influence of the centroid shift with field position. At some point, the imaging will be influenced due to the effective source no longer being centered in the pupil for off-axis field points.[4] The relay can also tailor the uniformity at the reticle to counter such influences as coating performance by designing in distortion. Distortion is a change in magnification with field, which also means a change in NA with field. The amount of distortion allowed is limited to the degree of partial coherence variation across the field that the lithography can accept.

5. SUMMARY

The technology behind the mass production of micro-electronics is impressive, and it is no surprise that the requirements of microlithographic illuminators are so stringent. This work covers peripherally the methods and importance of the illuminator's shaping the effective source and producing a uniform field for tight dose control in the lithography. Also covered in light detail is the design of the illuminator, with discussion the methods of designing the illuminators. All of these subjects are covered, along with methods of design, in more detail by the author in a longer treatise.[2] A final note is that there are many applications other than microlithography that use illuminators and do benefit from the techniques and methods discussed, such as inspection systems of wafers and reticles, and flat panel fabrication.

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