Optical Lithography - Thirty years and three orders of magnitude
The evolution of optical lithography tools

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ABSTRACT

The evolution of optical lithography is traced back more than 30 years to its beginnings with contact printing. As the complexity of integrated circuits increased, the intolerance for defects drove the industry to projection printing. Projection printing was introduced in the early 1970's by imaging the full wafer at 1:1 magnification. The rapid increase in wafer sizes was accommodated by annular field scanning using 1:1 imaging mirror systems. Decreased linewidths and tighter overlay budgets combined with larger wafers created huge difficulties for the mask maker which weren't relieved until the introduction of reduction step-and-repeat printing of small blocks of chips in the late 1970's. Further demands for smaller linewidths and larger chips have driven optical lithography to shorter wavelengths and to scanning the chip in a step-and-scan printing mode. Future advancements in lithography will likely combine novel scanning techniques with further reductions in wavelength.

1. INTRODUCTION

Accommodating the exponential growth of microcircuit components required optimizing the image transfer process from the mask to wafer. This is complicated by the competing dynamics of smaller features, larger chips and larger wafers. Today, *Moore's Law* is recognized as the defining explanation for the exponential growth of nearly anything related to the semiconductor industry. Optical lithography has followed Moore's Law[1], but it is becoming increasingly more difficult to stay on the curve in spite of its *validity* for the past 30 years. What follows is a personal perspective of the evolution of optical lithography and a rationalization of its development over the last 30 years. It is instructive to trace this evolution in an effort to better understand potential future options.

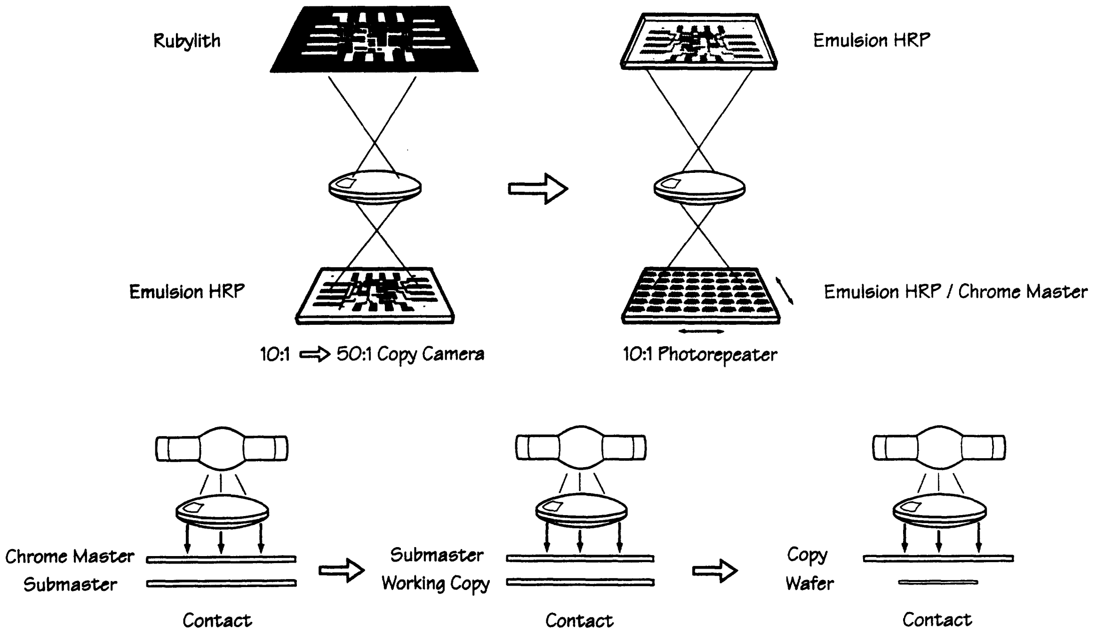

Figure 1. Wafer Lithography as practiced in the mid 1960's

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2. CONTACT PRINTING

Let us start the discussion from the mid 1960's when the process for transferring patterns onto the wafer was dominated by contact printing. Figure 1 diagrams the lithography process in use at that time[2,3]. Rubylith, a lamination of dark red and clear plastic foils was used to define the master pattern for replication. A starting scale was chosen such that the integrated circuit layout could be delineated with sufficient geometric accuracy by pealing off the red plastic features representing circuit details with a razor blade and straight-edge. The accuracy of this process was approximately 100-200 um and the circuit pattern (in the early 1960's) was usually no larger than the standard drafting board. This master pattern was then reduced in size onto a high resolution photographic plate with a large format copy camera used "backwards". The reduction ratio was in the range of 10-50:1. The photographic plate was then developed and used as a master pattern in a reduction photorepeater (usually 10:1) which replicated the circuit pattern hundreds of times onto another high-resolution photographic plate. This plate served as a contact printing master. This master mask was too valuable to use directly so sub-masters were made from which working copies were produced. The size of the production run determined the number of working copies required. Working copies were used from 1-25 times depending on the complexity of the circuit and its vulnerability to defects from contact. The need for more robust master masks led to the conversion of photorepeaters from a photographic emulsion medium to photoresist on chrome. The switch was made because silver-halide emulsion is soft and fragile whereas a chrome-on-glass pattern is extremely robust and, unlike emulsion, could be cleaned and reused many times.

The mask making process has gone through a fascinating evolution in itself which we do not have the space to elucidate here. Greater detail can be found in a recent account by Levy[4]. Suffice it to say that the clumsy process described above was quickly replaced by several approaches to computerized and automated optical pattern generators which has been described by the David W. Mann Company in 1968[5], Bell Laboratories in 1970[6] and Philips in 1972[7]. These systems took advantage of the availability of the first affordable digital computers for the real-time management of large volumes of data and machine control. Computerized optical pattern generators eliminated manual layout and streamlined the process of creating the integrated circuit master pattern.

3. LENSES FOR MASK MAKING

The first major challenge to optical technology came during this same period (mid 1960's) with the manufacture of lenses used in copy cameras and photorepeaters. These lenses required very tight control of distortion and necessitated state-of-the-art component fabrication and assembly. Lenses were available from a number of companies but the quality was highly variable. Compared to microscope objectives, these lenses were perhaps the first large field multi-element lenses requiring diffraction limited performance and uniformity of imagery across the field. Previous applications which required microscope objectives or traditional camera and enlargement lenses tolerated the normal axial *sweet-spot* and falloff in performance at the edge of the field. Achieving simultaneously high uniformity of imagery and high geometric accuracy in an image was a very tall order. It was at this time that lens design codes and computers were stressed to be able to handle the optimization of such complex lenses. The design task required simultaneously optimizing 20-30 variables.

Photorepeater lenses for imaging in emulsion were usually designed to operate at the mercury e-line (577nm). Photoresist materials more naturally operated in the blue so the lens designs and glasses were optimized for operation at the mercury g-line (436 nm). Many companies struggled with the difficulties associated with designing and manufacturing these lenses including Bausch and Lomb, Bell Laboratories, Cerco, Fuji, IBM, Leitz, Nikon, Olympus, Tropel, Wray and Zeiss, but few were willing to discuss the details[8]. The introduction of the single-mode HeNe laser interferometer dramatically influenced the manufacture of these precision lenses[9].

It was not uncommon for lens manufacturers to provide its lenses to a variety of equipment manufacturers since the lenses were often built to loosely agreed upon dimensional standards established by the lens manufacturers. A vintage 1968 step-and-repeat system for mask making is shown in Figure 2a. This system could use a selection of lens magnifications interchangeably or simultaneously to print different circuit patterns and test patterns on the mask. Figure 2b shows a production mask contact copier for producing sub-masters or working copies.

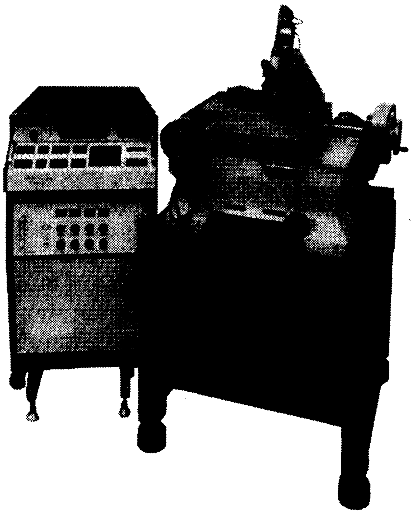


Figure 2a. Jade step-and-repeat mask maker

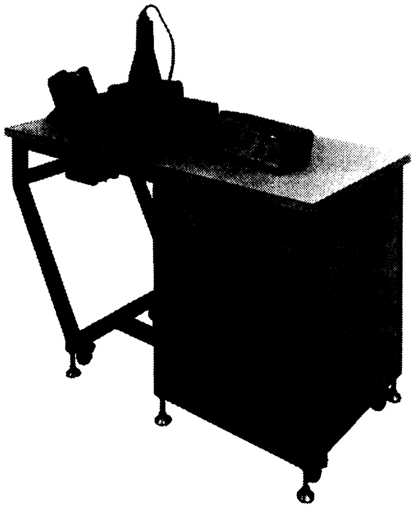


Figure 2b. Jade photomask contact copier

4. PROXIMITY PRINTING

The problem with contact or near-contact (proximity) printing is the inevitable transfer of defects from the mask to wafer or wafer to mask. Physical contact clearly reduced wafer yield and was the major impetus for the development of projection printing directly onto the wafer. The tradeoff encountered when moving off contact was reduced resolution. Minimum resolution is related to the mask-to-wafer gap, g, by

$$R = k\sqrt{\lambda g}, \tag{1}$$

where $k \approx 1$. This also clearly explains the value of a smaller wavelength λ, although the resolution improvement is not in linear proportion as with projection imaging. The lure of the delightfully simple concept of shadow printing to produce resolutions below 1um at reasonable gaps drives the needed wavelength to the 1nm region. This falls within the realm of x-ray lithography which has been summarized nicely by Smith[10].

5. 1:1 FULL-WAFER PROJECTION PRINTING

A number of companies developed systems for imaging the full wafer including Canon, Nikon, Olympus, Optimetrix and Telefunken. One early system representative of the era was the Canon PPC-1 shown in Figure 3a. Figure 3b shows the cross-section of the lens used in that system. It is a double-Gauss form operating at the g-line at a numerical aperture of 0.14 and was specified to provide 2-3um imagery on wafers up to 50mm diameter. This lens was well corrected but not telecentric. It soon became clear that the lack of wafer flatness and the inability to precisely set focus created overlay errors with lenses that were not telecentric. A telecentric lens is designed so that the central or chief ray is normal to the image plane everywhere in the field, not just on axis. Optical technology for 1:1 wafer imaging with refractive lenses was not particularly challenged for image fields up to 35-50mm wafers. For wafers larger than 50mm diameter, lens production became much more difficult, particularly with telecentricity as a new requirement. Figure 4 shows one such telecentric design proposed by Perkin Elmer in 1970[11]. Telecentricity created the need for new approaches.

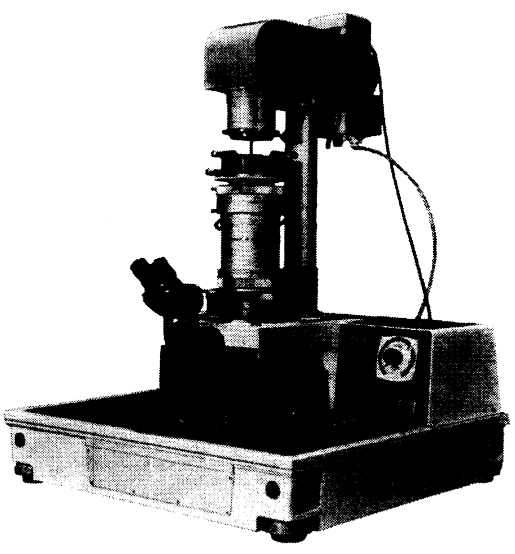
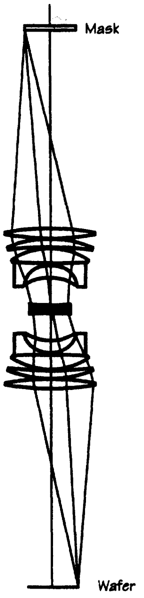


Figure 3a. Canon PPC-1



Full Wafer Imaging

50 mm ϕ field

$\lambda = 436$ nm, NA = 0.2

$W = 2\ \mu m$, $N = 1 \times 10^8$

Figure 3b. Canon PPC-1

The Dyson 1:1 optical design[12], invented in the late 1950's for replicating diffraction gratings, and later achromatized for microcircuit imaging[13], provided a good short-term solution for 1:1 wafer imaging. Unit magnification imagery, with a symmetric optical design, is completely free of distortion, coma and lateral color because of symmetry. This relieves the optical designer of the difficulty of correcting these aberrations, but this advantage only results if through manufacturing, perfect symmetry is retained. The Optimetrix Company was the first to exploit the Dyson design and introduced two generations of the *Unimag* optical system, the last of which is shown in Figure 5. Tropel manufactured the lens and illuminator. This lens represented the highest imaging performance achieved without scanning or stepping and terminated the evolution of static 1:1 full-wafer imaging systems. A small number of systems were produced and this approach was discontinued soon after the wafer scanning approaches took hold.

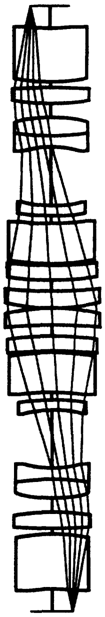
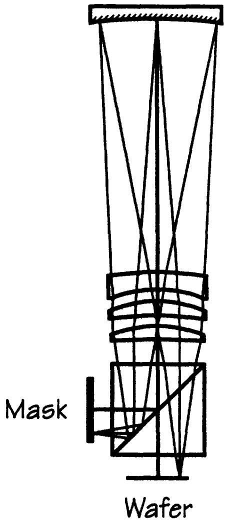


Figure 4. The Perkin Elmer Trans-300 Lens



Full Wafer Imaging

75 mm ϕ field

$\lambda = 436$ nm, NA = 0.2

$W = 1.8\ \mu m$, $N = 3.4 \times 10^8$

Figure 5. The Optimetrix Unimag Design

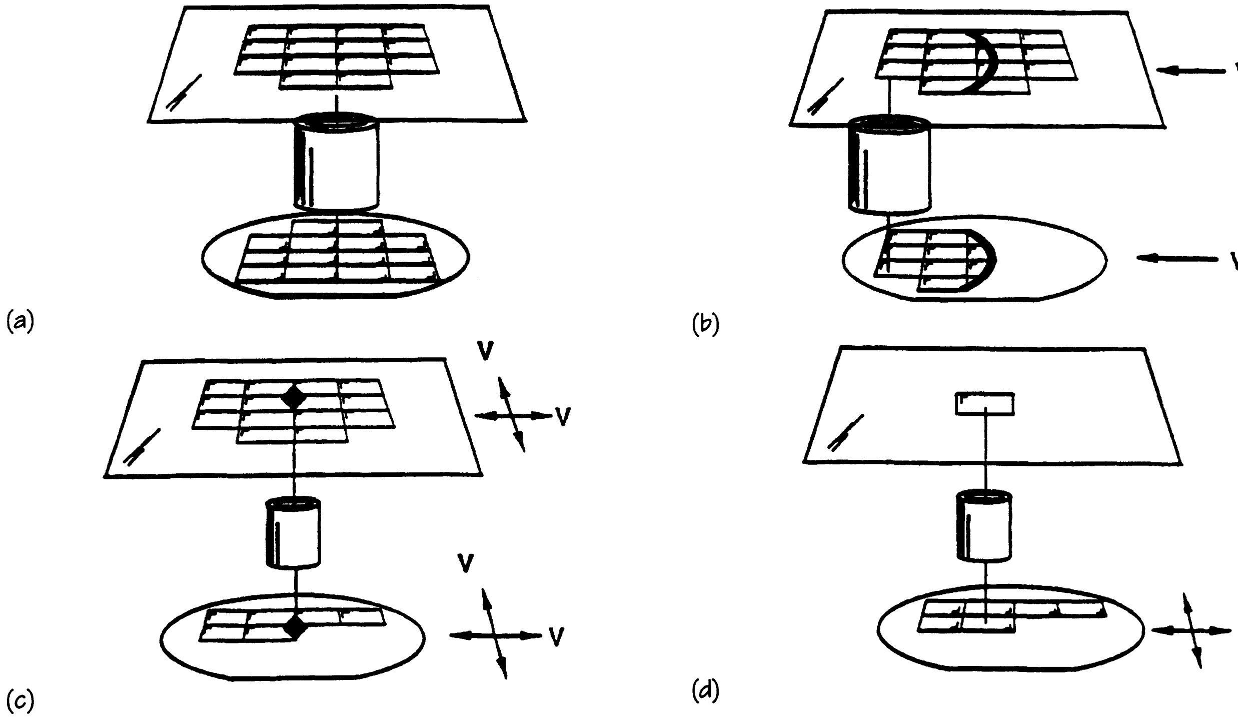


Figure 6. Image partitioning methods at 1:1 using (a) 1:1 full wafer static imaging, (b) full wafer annular field scanning, (c) 1:1 raster scanning and (d) 1:1 step-and-repeat.

6. 1:1 FULL WAFER SCANNING

About the same time as the Unimag (1974), Perkin Elmer invented an elegant approach to unburdening the optical system in trade for a more complex mechanical system[11]. This is one of several approaches to partitioning the image as shown in Figure 6. Most of these approaches were demonstrated, but not all were successfully commercialized. Perkin Elmer's system was called the Micralign. This system was based on a symmetric, nearly concentric, all-reflective telecentric relay of 0.16 NA. This design was very well corrected over a narrow annular field region of about 1mm width which could print wafers up to 100mm diameter at 2-3um resolution. The geometry of the optical system is shown in Figure 7. The optical system is capable of transferring a huge number of pixels because only a small annular portion of the field needs to be well corrected. This annular strip is scanned transverse to the annulus, sweeping out the full area of the wafer. The optical system is very simple incorporating only two spherical mirrors; the concave mirror is used twice. Plane mirrors are used to bring the object and image planes to useful positions so that the mask and wafer can be scanned and maintained in optical alignment and focus. The one-dimensional scanning mechanism is a simple flexure pivot which traces out a long radius arc. One of the plane mirrors is a 90° roof mirror to orient the image on the wafer the same as a contact print.

Two other companies developed products similar to the Micralign but with different optical folding arrangements and scanning stages. Canon's system was introduced in 1979 with a different folding arrangement and wafer orientation as shown in Figure 8. Cobilt introduced a system in 1978 with mask and wafer in the same plane as shown in Figure 9.

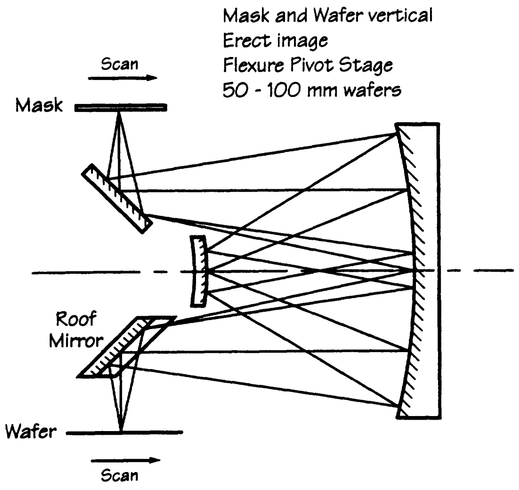


Figure 7. PE Micralign 100 (1975)

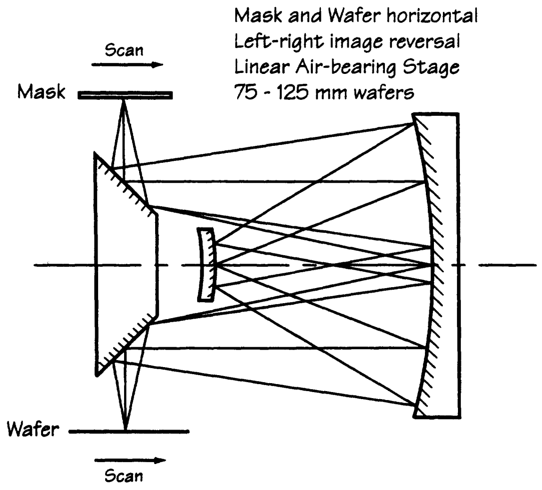


Figure 8. Canon MPA-500FA (1979)

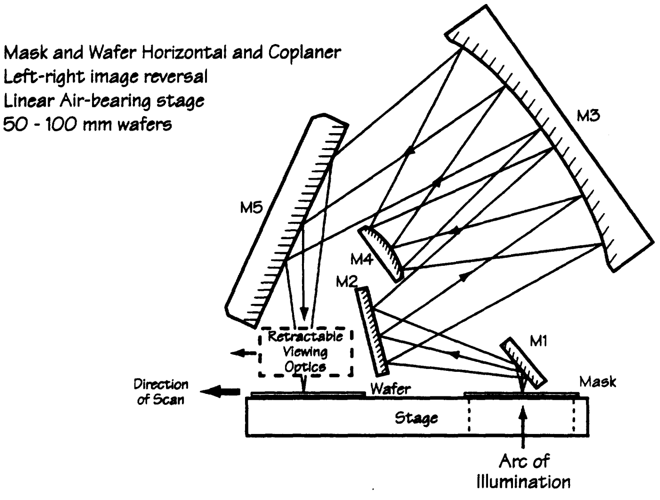


Figure 9. Cobilt CA-3000 (1978)

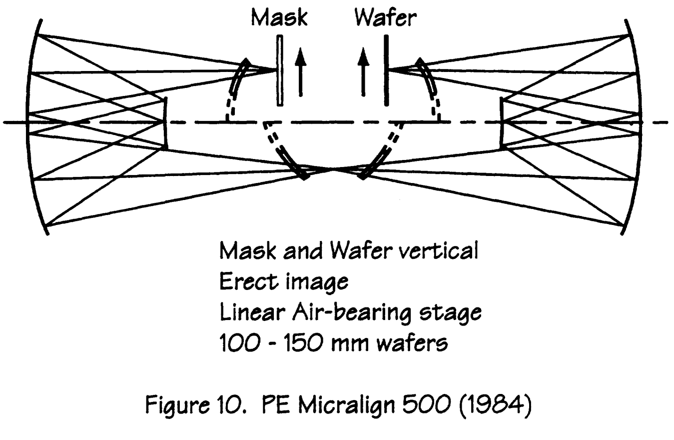
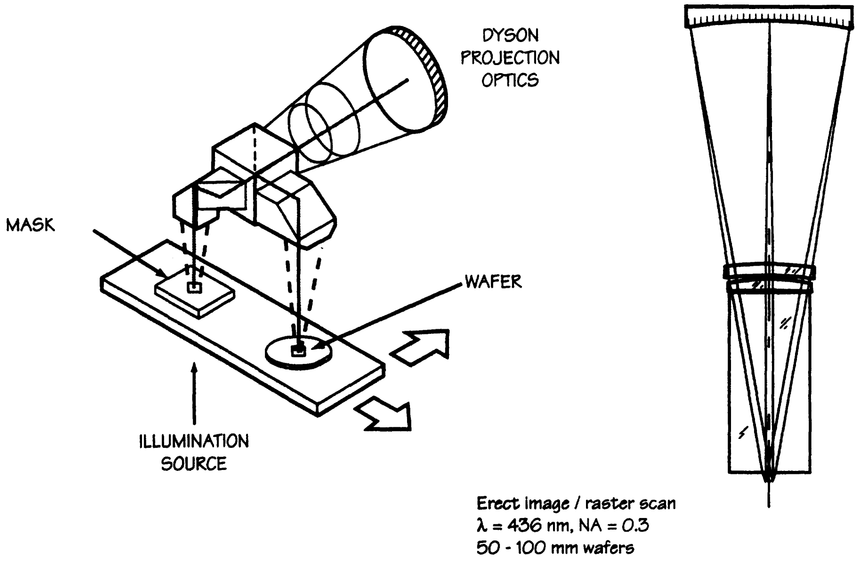


Figure 10. PE Micralign 500 (1984)

The Perkin Elmer system was quite successful and evolved over several generations of systems capable of exposing wafers up to 150mm diameter with resolutions down to 1.2um by isolating the shorter 250nm radiation from the mercury lamp illuminators. The 150mm wafer machine was composed of two Offner relays arranged back-to-back to achieve a larger field and incorporated several concentric shell elements for improving the optical correction and providing a mechanism for tuning magnification and astigmatism. This arrangement, shown in Figure 10, permitted the mask and wafer to ride on a simpler more rigid linear air-bearing stage which allowed elimination of the fold mirrors. This approach eventually reached its technology limits due to large overlay error contributions from the tool and masks. Overlay was limited by tool setup and stability as well as form errors in the mirror surfaces. The structure housing the large 19" diameter concave mirrors was a voluminous invar casting purged with Helium. The overlay rule of 20-30% of the CD became too difficult to maintain over the area of the entire wafer relative to reduction steppers which operated over much smaller fields. A distinct advantage of an all-reflective design is the very broad bandwidth radiation which can be imaged without chromatic aberration, but resolution was limited to 1.2um at 250nm wavelength since the numerical aperture of the design was limited to 0.16. Over 2000 Micralign systems were produced and a large fraction are still in operation.



Erect image / raster scan
λ = 436 nm, NA = 0.3
50 - 100 mm wafers

Figure 11. Bell Laboratories Scanning Projection Printer (1976)

7. 1:1 RASTER SCAN

At the time of the introduction of the Micralign, an alternate approach was under development at Bell Laboratories for scanning the wafer and mask in *two* dimensions with a small field lens derived from the Dyson optical design. The system was called the scanning projection printer or SPP. The lens was designed by Tropel to operate at a 0.3 NA at the g-line and of such a scale that the mask and wafer (up to 100mm diameter) were in the same plane. The object and image were 7mm diamond-shaped fields which overlapped by 50% on adjacent scans so as to create a uniform exposure. A complex prism arrangement was required for proper orientation of the object and image as well as to separate them by an amount adequate for future wafer sizes. The system is shown schematically in Figure 11. This arrangement was inhibited by the large amount of glass which introduced focus shifts during exposure due to absorption that were difficult to anticipate and compensate. Throughput was limited by absorption.

Other more compact approaches to scanning Dyson systems were proposed but never built for wafer exposure. Similar approaches have been applied to flat panel printing. These early systems, in retrospect, were mechanically too complex and expensive to produce relative to other commercial equipment at the time. The tolerance to yaw in the scanning stage was particularly challenging.

8. 1:1 STEP-AND-SCAN

Perkin Elmer recognized the eventual difficulties of 1:1 scanning for increasingly larger wafers and had the wherewithal to extend their technology to annular-field scanning over a sub-field. To implement this approach, a scaled-down lens, similar to that of Figure 6(b) would have an annular field with a height equal to one or several chips. Instead Perkin Elmer chose to extend the scanning approach to include reduction. This was a bold step and is covered in Section 11.

9. 1:1 STEP-AND-REPEAT

An obvious alternative to 1:1 wafer scanning or full-wafer printing is to step the image of one or more chips directly onto the wafer since this approach was successfully used to create the pattern arrays for contact printing masks. One might have expected 1:1 stepping to proceed reduction stepping, but, in fact, this was not the case. Ultratech introduced a 1:1 stepper in about 1980. The system was based on the Wynne-Dyson optical design shown in Figure 12.

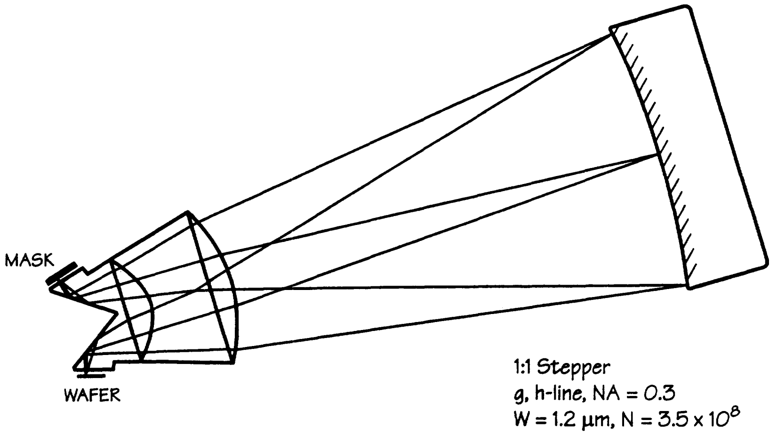


Figure 12. Ultratech Wynne-Dyson 1:1 stepper (1980)

The object and image planes are made accessible by prisms which separate the object and image planes in angle by 22 degrees. This arrangement does not use the center of the field but the large annular-field region is maximized in area when the exposure area is a rectangle with an aspect ratio of about 2:1. This design has been scaled up to field sizes as large as 22x44mm which operate at the g-line and h-line wavelengths as well as i-line versions. While the optical design is simple and incorporates only a few surfaces, the large scale of the system and *small* number of air spaces and lens thicknesses present unique materials and manufacturing challenges.

The very best part of the image field of the Wynne-Dyson design is not used in the arrangements described because of the incorporated prisms. A clever arrangement which overcomes this disadvantage is called the Half-Field Dyson[15]. This approach, as shown in Figure 13, separates the object and image planes by a small displacement along the optical axis (slightly disrupting symmetry). This design is an elegant solution for very high performance 1:1 imaging but has not been commercialized due to the need to develop a unique 1:1 reflective mask technology. As is well known, the semiconductor industry stubbornly resists changes that are not either evolutionary or absolutely necessary. This is for good reason since semiconductor lithography is but one process in a long chain of weak links and nearly any unnecessary change represents a poor business risk. Nonetheless, the potential performance of the half-Dyson is impressive. The system proposed had an NA of 0.7 operating at 248nm. A prototype version of this imaging system was demonstrated at 193nm[15].

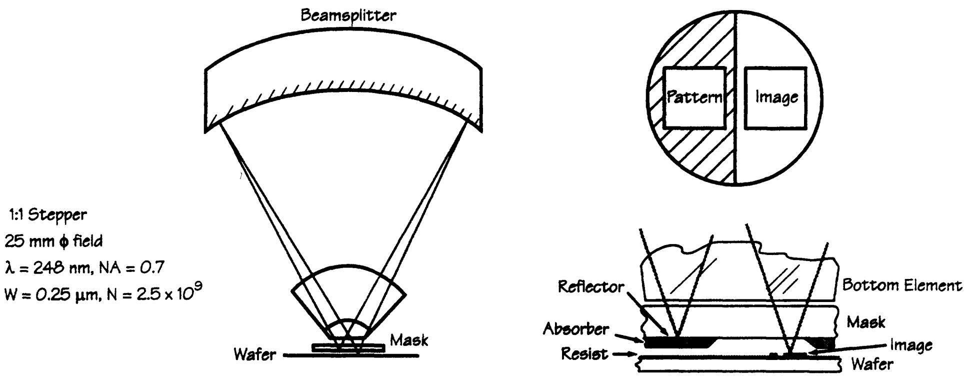


Figure 13. Half-Field Dyson 1:1 stepper

Mask making problems associated with sub-micron imaging at 1:1 are very challenging and introduce the need for proximity correction on the mask. This limitation is also encountered in x-ray proximity printing whose performance will likely be limited by mask-making difficulties. If the pattern transfer process from mask to wafer can be achieved at a reduction, tolerances on the mask are reduced by the reduction ratio.

10. REDUCTION STEP-AND-REPEAT

Telefunken introduced the first reduction imaging system for wafers in 1968. This equipment incorporated a 2:1 reduction lens complete with alignment capability[3], but was not a stepper. At the time, wafers were still quite small (35-50mm diameter). Step-and-repeat systems during this time were deployed only for creating the masks which were then contact printed onto the wafer.

Kasper was one of the first companies to offer wafer stepper systems with alignment capability and a choice of reduction lenses with reduction ratios of 2:1, 4:1 and 10:1. These systems were not very successful due to the lack of reliable alignment capability and automation. It wasn't until 1978, when GCA formally introduced the 4800 DSW with the automation of wafer handling and alignment that reduction stepping directly onto the wafer became practical. The first system introduced used Zeiss lenses operating at the g-line with a 0.28 numerical aperture, a 10:1 reduction ratio and an image field size of 10x10mm. This system is shown below.

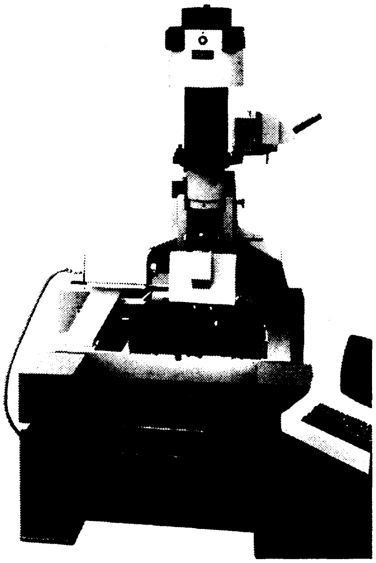


Figure 14. GCA 4800 DSW 10:1 Step-and-repeat system (1978)

Reduction step and repeat lithography marked the beginning of an amazingly rapid development period in optical imaging science and technology. Wafer sizes in the early 1980's were 75-100mm but, unlike scanners, steppers can print larger wafers without redesign of the stepper lens. Evolution of the technology is clear as long as the field size of the lens is large enough to contain one or more chips. When the chip size exceeds a practical lens field size, further partitioning of the image is needed. Figure 15 summarizes several image partitioning methods for reduction lithography[16]. Most of these approaches have analogies at 1:1 as illustrated in Figure 6.

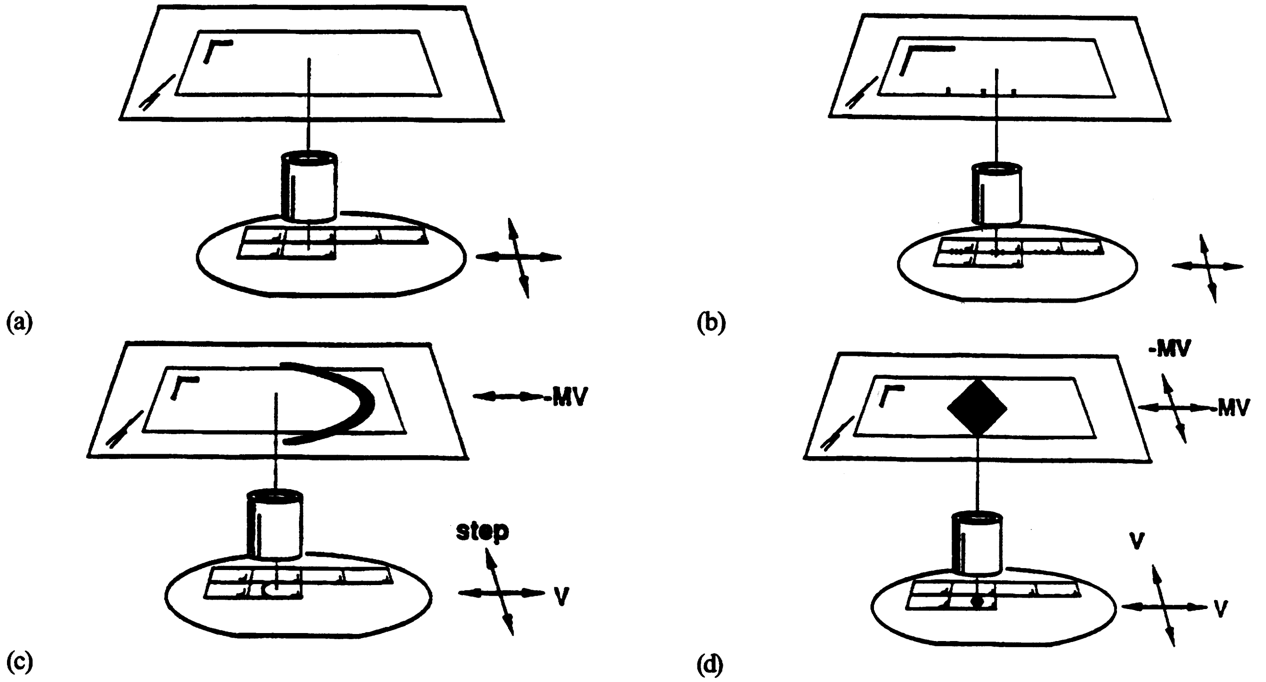


Figure 15. Reduction image partitioning methods using (a) M:1 step-and-repeat, (b) M:1 stitch-and-repeat, (c) M:1 step-and-scan and (d) M:1 raster-scan.

Figure 16 illustrates the rapid evolutionary development of reduction lenses. This Figure shows a small selection of lenses produced by Tropel, and drawn to the same scale. The successively larger sizes are a result of both larger image field sizes and higher numerical apertures.

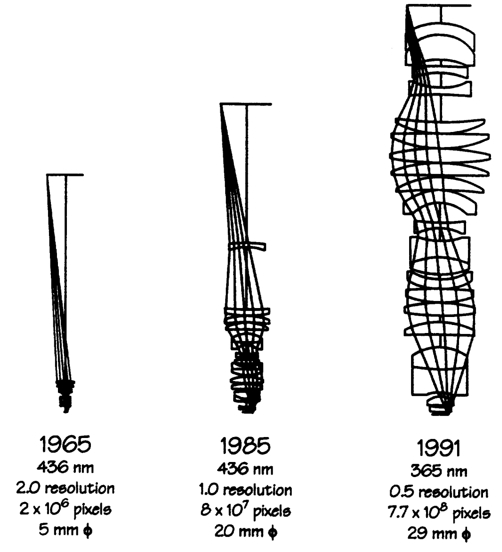


Figure 16. Development of lithographic reduction lenses

The photorepeater lenses of the mid 1960's were quite small. By the late 1980's, the size of lenses grew to the point where they could no longer be lifted or handled conveniently by assembly workers. As a result, all tooling and assembly methods had to change. For proprietary reasons, contemporary lens outlines are rarely shown, but for comparative purposes, the i-line lens shown for 1991 has an overall length of 800mm from object to image. Several of the lithographic lens manufacturers today have extended the object to image distance to 1000mm and the number of elements to more than 30.

Useful figures of merit for lithographic lenses are the number of printable resolution elements within the field of the lens, N, and the resolution limit R. N is calculated from the area of the image divided by four times the area of a resolution element:

$$N = \frac{A_{image}}{(2R)^2}, \tag{2}$$

Resolution R is given by:

$$R = \frac{k_1 \lambda}{NA}, \tag{3}$$

where k_1 is a process dependent factor in the range $.4 < k_1 < 1$.

Other significant trends are the dramatic improvements in optical design and manufacturing. As minimum linewidth or CD requirements pushed numerical apertures to levels higher than about 0.3, optical designers required the correction of successively higher orders of aberrations. Reducing the variation of CD over the image field requires successively better relative correction of aberrations. Since on-axis aberrations have fundamentally different symmetries than off-axis aberrations, the only way imaging off-axis and on-axis can be identical is when all aberrations are identically zero. In addition, correction of distortion to levels of less than 50nm over field diameters of 20-30mm requires manufacturing tolerances and lens element surface errors to levels *tighter* than that required for good image fidelity. Stringent CD-control and overlay requirements set transmitted wavefront tolerances to values tighter than the classical diffraction limit; i.e., $<\lambda/10$ vs. $\lambda/4$. Hence, the geometric perfection of the lens must *exceed* the diffraction limit. This becomes relatively more difficult as the resolution and field size of the lens increases. Higher resolution requires higher NA's and shorter wavelengths or both. Depth of focus or *DOF*, however, diminishes relatively more rapidly with numerical aperture. The total range of *DOF* for a well-corrected lens is given by: $DOF = k_2\lambda/(NA)^2$ where $k_2 \approx 1$.

In 1985, the first all-fused-silica reduction stepper lens operating with a line-narrowed 248nm KrF excimer laser, demonstrated 0.5um imagery over a 1cm x 1cm field and the elimination of the need for color correction[17, 18].

11. REDUCTION STEP-AND-SCAN

There comes a point when the field of a stepper lens is challenged by the demand for still larger chips. Semiconductor manufacturers generally prefer to place more than one identical chip pattern on the mask so that the mask can be inspected for defects by simple comparison techniques. A stepper printing a defective single chip reticle could render entire wafers useless.

The next logical progression to partitioning a lithographic image might be to break the chip mask into, say, two halves and "stitch" the two halves together in separate exposures[19]. A more flexible approach is one which scans an annular field or a strip field the full height of one or more chips[19,20]. This is illustrated in Figure 15c. The first (and only) annular field reduction step-and-scan system was designed and built by Perkin Elmer and labeled the Micrascan I[20]. The optical design of the system is shown in Figure 17. Illumination was provided by a Mercury lamp with a bandwidth of 10nm centered about 250nm. The numerical aperture was modest at 0.35, but the lens was nonetheless the most complex optical and mechanical system of its time. The advantage to partitioning the image is to affect a more cost effective and/or better technical tradeoff of manufacturing difficulty and performance. This particular implementation strained the concept and only a small number of systems were produced.

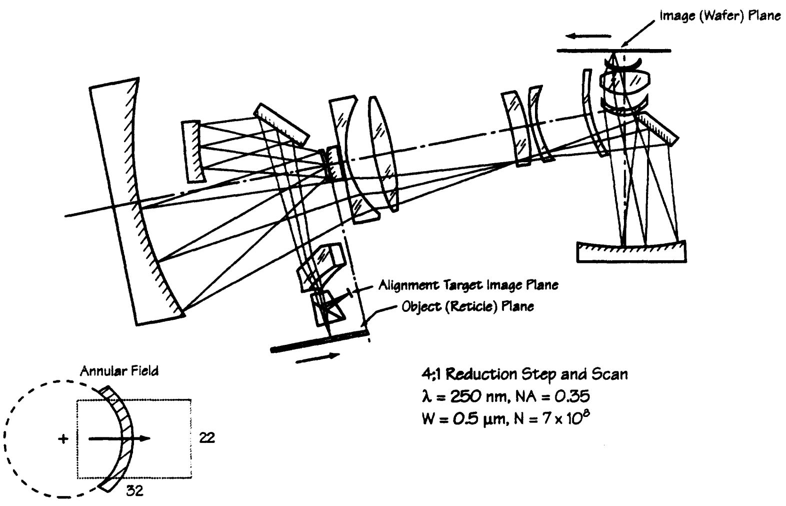


Figure 17. Perkin Elmer Micrascan I (1989)

A simpler approach is to scan a strip field from a conventional stepper lens[20]. An unpublished design study showed there is no benefit to an annular field when the numerical aperture requirement exceeds about 0.35[21]. SVGL (previously Perkin Elmer) then moved to an on-axis, full-field catadioptric design for the Micrascan II[22] and Micrascan III[23] as shown in Figures 18(a) and 18(b). SVGL achieved very broad-band color correction by incorporating a beamsplitter and spherical reflecting surface into the optical design. The spherical reflector provides a large proportion of the optical power without introducing color aberrations. This allowed correction of chromatic aberrations over a 20nm bandwidth of a mercury lamp centered at 250nm for a numerical aperture of 0.50. The Micrascan III, with its still higher numerical aperture of 0.60, required the bandwidth of the KrF excimer laser source to be narrowed to about 70pm to eliminate chromatic aberrations. While small, this is still about 100 times broader than an all-fused silica refractive lens of equivalent numerical aperture.

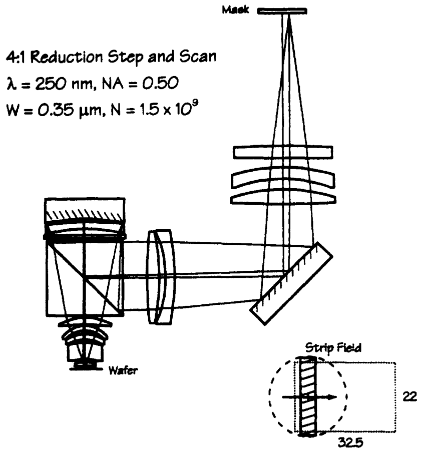


Figure 18(a). SVGL Micrascan II

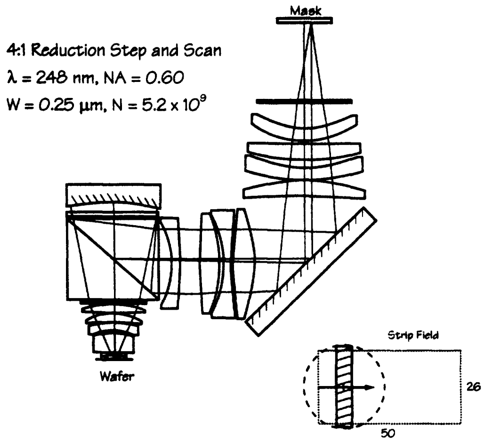


Figure 18(b). SVGL Micrascan III

A lens designed for exposing a strip-field need only be about 70% of the scale of a full-field lens. This has significant benefits in relation to today's expensive deep-UV lenses. Since this is a linear scaling, the volume of glass needed and hence the cost, would be about one third ($.7^3$all else being equal). Fused silica for DUV lenses, because of very stringent homogeniety (<1 ppm) and purity requirements, costs several thousand dollars per pound!

12. REDUCTION RASTER-SCAN

If the chip size becomes larger than a practical field size for lenses in a step-and-scan mode as discussed above, one can partition the image further by scanning both object and image in two dimensions as shown in Figure 15(d). This arrangement would require mechanical control of reticle and wafer stage motions at precisely the reduction ratio. This concept was first demonstrated using a 10x microscope objective to cover an image field of 10x10mm[24].

13. SUMMARY AND FUTURE DEVELOPMENTS

To date, optical lithography has evolved by *natural selection* to what seems to be a common technique from two different branches - namely reduction step-and scan. An evolutionary tree which summarizes the developments we have discussed is shown in Figure 19.

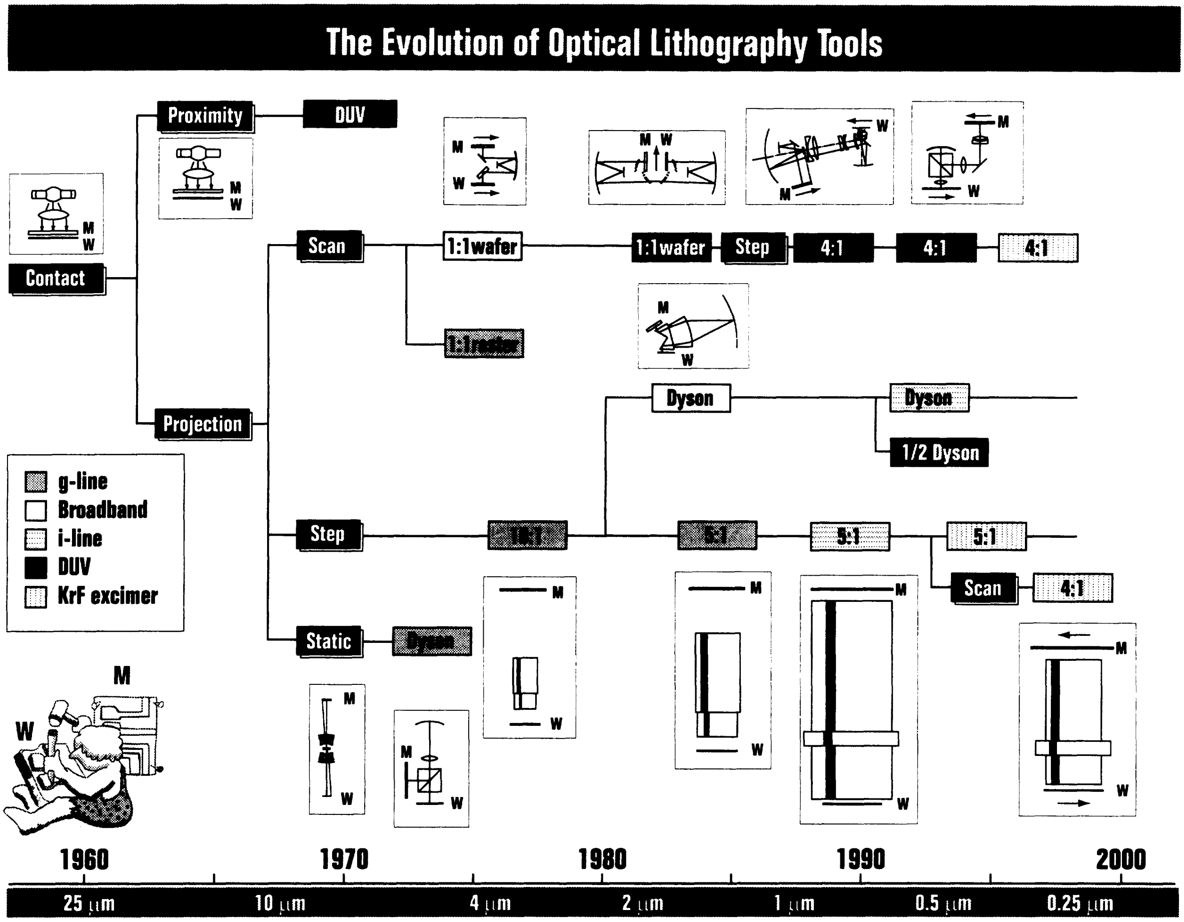


Figure 19. The Evolution of Optical Lithography

There are clearly many options for sub-micron lithography for the future, but the winning approaches will, of necessity, be those which can integrate most cost effectively into future manufacturing processes with the minimum of disruption. I-line lithography will likely evolve to 0.3um with resolution enhancement techniques. The cost effective high-pressure mercury light source is likely to remain for quite a long time. KrF excimer laser systems at 248nm should carry production steppers from 0.3um down to 0.18um or perhaps smaller with resolution extension techniques and illumination system improvements. The ArF excimer laser at 193nm has great promise if the technology base built up at 248nm can be extended without major optical material or laser problems. With more advanced lens designs and scanning approaches 193nm systems should evolve to be the production tool for 0.1um device generations. Initial results with prototype high NA lenses at 193nm show great promise and suggest more headroom remains[25,26].

Below 0.1um, more exotic lithographies may be needed, but the more evolutionary approaches will be preferred. A promising but hardly evolutionary approach is EUV (extreme ultraviolet) reduction step-and-scan at 11 or 13nm. Significant problems remain which are low reflectivity mirror coatings, the need to produce multiple aspheric mirror surfaces to <1nm accuracy, cost effective high-output EUV sources, robust resists for these wavelengths and a defect-free or repairable reflective mask technology. If in ten years we can achieve this or its resolution equivalent, we stay within Moore's Law!

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