

Silicon Processing

for the VLSI Era
Volume 1 – Process Technology

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LITHOGRAPHY II:

OPTICAL ALIGNERS and PHOTOMASKS

In the previous chapter, the material properties of photoresists and their processing technology was covered. In this chapter, we describe the remainder of the topics involved in transferring patterns to the silicon wafers, including: a) the equipment used to project the image of the patterns onto the wafer surface (i.e. so-called *aligners* or *printers*), thereby allowing the photoresist at the desired pattern locations to be exposed; and b) the pattern transfer tools that contain the patterns to be printed onto the photoresist-coated wafers (i.e. the photomasks and reticles). As a prelude to the description of aligners or masks, we briefly present some optical theory which is used to design and describe the operation of aligners, and which underlies the specifications of masks and reticles.

Even before beginning the discussion on optics, however, it is useful to identify the key issues of microlithography hardware. That is, the most important characteristics of the machines and masks used to project the image of patterns onto wafer surfaces are the following: a) resolution; b) pattern registration capability (alignment); c) dimensional control; and d) throughput.

In general, the term *resolution* describes the ability of an optical system to distinguish closely spaced objects. Specifically, we will refer to the *minimum resolution* of a microlithographic printing machine as the dimension of minimum linewidth or space that the machine can adequately print (or *resolve*). We will see, however, that such a minimum dimension also depends on the photoresist and etching technology, as well as the resolution of the aligner. The subject of resolution will be dealt with more thoroughly in the section on *Optics of Microlithography*, but it is important to emphasize that *high resolution* is usually the most sought after property of an aligner.

The *pattern registration capability* is a measure of the degree to which the pattern being printed can be "fit" relative to a previously printed pattern. As the feature sizes are so small in microlithographic applications, and the number of layers that must be correctly fit on top of one another is large (e.g. 10-15), a very tight fit indeed is required.

The *dimensional control* requirement in microlithography refers to the ability to produce device feature sizes over the entire wafer surface with high accuracy and precision. In order to accomplish this task, the feature patterns must first be correctly reproduced on the pattern transfer tools (masks and reticles), and then be accurately printed (imaged and etched) onto the wafer surface.

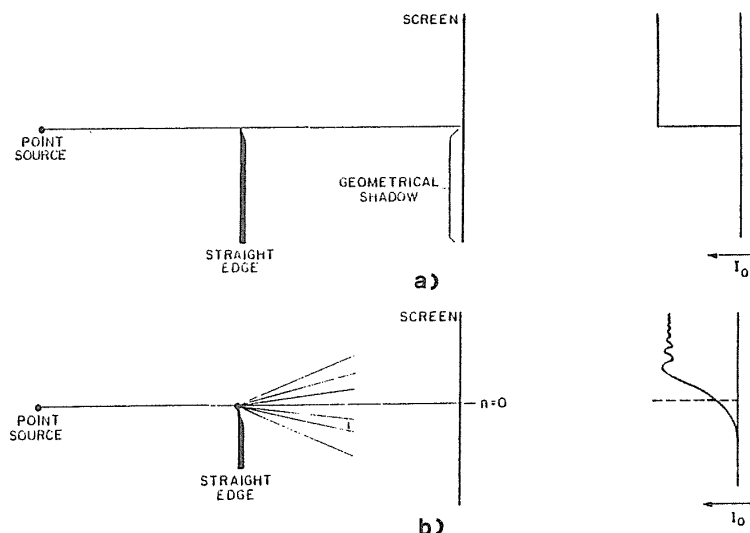


Fig. 1 Intensity distribution produced by a spatially coherent ray of light as it passes by a straight edge: (a) according to geometrical optics; (b) with diffraction. Reprinted with permission of Ref. 1 Copyright 1983, American Chemical Society.

The *throughput* of the pattern transfer process is an important, but not always overriding, process characteristic. For example, if a device can only be fabricated on a low-throughput, but high resolution printer, it may still be economically sound to carry out the fabrication on such a machine. Nevertheless, in most production applications the throughput of a process or machine is very important, and the selection of one machine over another may be decided by this factor.

OPTICS OF MICROLITHOGRAPHY

In VLSI fabrication, the resolution of the optical lithography printing system is of major importance, since it is the main limitation of minimum device size. In modern projection printers the quality of the optical elements is so high that their imaging characteristics are limited by diffraction effects, and not by lens aberrations (i.e. they are said to be *diffraction limited* systems). Since the resolution is determined by diffraction limitations, and it is necessary to have an understanding of some concepts surrounding diffraction limited optics including coherence, diffraction, numerical aperture, modulation, and most importantly the modulation transfer function. It is the purpose of the following sections to present information on these subjects, although in a brief and fundamental manner. Consult Refs. 1 and 2 for more details.

Diffraction, Coherence, Numerical Aperture, and Resolution

All optical lithography systems involve light diffraction imaging, insofar as radiation is directed from an illumination source past an edge or through a slit (e.g. both features occur on photomasks). Due to diffraction effects, the radiation spreads into the region which is not directly exposed to the oncoming waves, and if projected on a screen, appears in patterns dependent on the diffraction effects (see Figs. 1 & 2). The intensity distribution produced on the screen may be a series of alternating light and dark bands, and is dependent on the distance

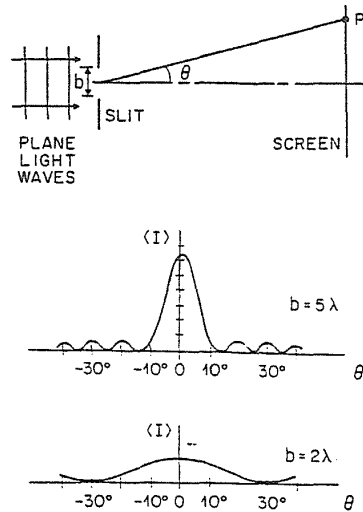


Fig. 2 Fraunhofer diffraction pattern of a single slit illuminated with monochromatic light; the intensity distribution is shown for two different slit widths. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

between the slit (mask) and the screen onto which the image is projected (e.g. a wafer surface), the geometrical configuration of the slit, and the chromatic purity of the illumination source. The chromatic purity of the radiation source is usually of little concern in microlithography, since most optical lithography systems use filters to select particular wavelengths, or employ resists that have been sensitized to a particular range of wavelengths.

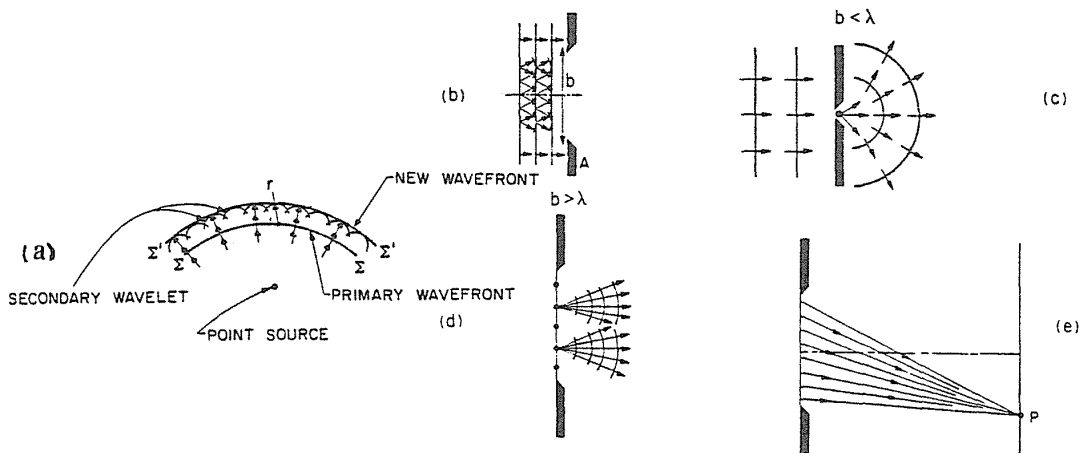


Fig. 3 (a) Schematic of Huygens Principle showing construction of a new wave front Σ' from the preceding wave front Σ ; (b) plane wave front incident on a slit of width b ; (c) diffraction for case where $b < \lambda$; (d) $b > \lambda$ showing subdivision of slit into distribution of Huygens sources; (e) superposition of waves at P. Reprinted by permission of Ref. 1, Copyright 1983, American Chemical Society.

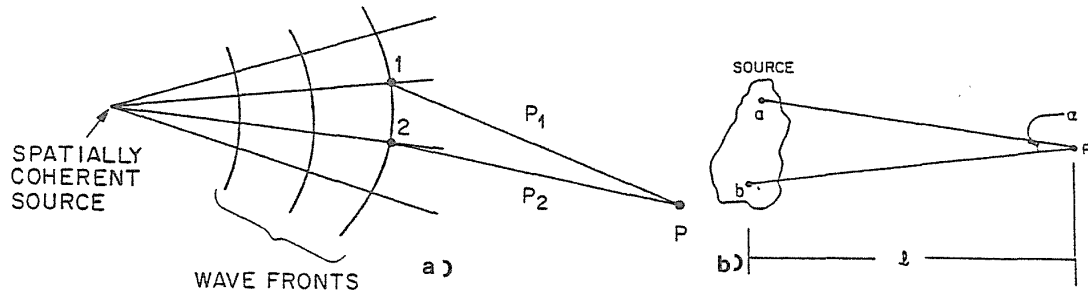


Fig. 4 (a) Schematic showing a perfectly coherent source. (b) An incoherent source of radiation of finite size. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

It is also important to point out at the outset that all the information contained in the edge of an image results only from the diffracted light.

If the distance between the screen and slit is short (i.e. in *contact* or *proximity* aligners), the form of diffraction which occurs is known as *Fresnel (or near-field) diffraction*. If the distance between slit and screen is large, *Fraunhofer (or far-field) diffraction* takes place. Because most modern optical lithography systems are *projection type systems*, in which the slit-to-screen (e.g. mask-to-wafer) distance is large, our discussion is limited to Fraunhofer diffraction.

Invoking Huygens' principle, each point on a wave front of light may be regarded as a new point source of waves. Each of these Huygens sources are in phase and equal in intensity. As shown in Fig. 3, when the primary wave front approaches a slit, new wavefronts are constructed from point sources at the slit. Representation of the number of sources is dependent upon the width, b , of the slit. The intensity profile that is imaged on a screen (shown in Fig. 2), results from summing all the radiation emitted by the sources at the plane of the screen. Figure 2 illustrates that for values of b larger than the wavelength λ , pronounced diffraction effects arise from the summation of wavefronts, arriving from different distances, at each point on a screen. This geometrical condition is encountered in current optical microlithography applications (i.e. $b \geq 1.0 \mu\text{m}$, $\lambda \leq 0.43 \mu\text{m}$).

Spatial coherency, s , is a measure of the degree to which the light emitted from a source is in phase at all points along the emitted wave fronts. A point source, of infinitely small dimension, represents an ideal coherent source (Fig. 4a). Because all lithography systems have radiation sources of *finite* size, the degree of coherence exhibited by light incident on a plane is dependent on the source size (Fig. 4b), its distance from the plane, and the angular range of lightwaves from the source allowed to pass through an aperture between the source and the plane. We will show later that perfect coherence is not needed, nor even advantageous (i.e. partial coherence is better), for imaging patterns with projection printers. This is fortunate, since the brightness of an ideal point source reduces to zero, and would require an infinite exposure time.

To determine the resolution capability of an optical system, diffraction gratings are typically employed, both experimentally and in mathematical analysis. Diffraction gratings consist of features of equal widths arranged at equidistant intervals (known as the grating period v). The grating can be treated as a series of diffraction slits which, when irradiated with coherent light, will emit identical diffraction patterns from each slit. (Note that in IC fabrication, one would not print a diffraction grating *per se*, but such features as a set of interconnect lines designed with dimensions equal to the resolution limits of the lithography system have essentially the same structure. Hence, the principles of this discussion are still valid.) The patterns interfere with each other to produce an intensity pattern on the screen, whose principal maxima are given by the

equation:

$$d \sin \theta_N = N \lambda \quad (1)$$

where: $N = 0, \pm 1, \pm 2 \dots$ is the order of diffraction; d is the distance between the slits; and θ_N is the angle at which the diffraction pattern exists. Note that the width of the principle maxima is determined by the number of slits used, and that the intensities of all the maxima are governed by the diffraction pattern of a single slit of width equal to that of any one slit used.

In any optical projection system the major factor that limits its resolution capabilities is the physical design of the objective lens and its numerical aperture (NA). The NA is a measure of a lens' capability to collect diffracted light from an object (photomask) and project it onto the wafer. The NA is defined by:

$$NA = n \sin \alpha \quad (2)$$

where n is the refractive index (typically 1.0 for air), and 2α equals the angle of acceptance of the lens (shown in Fig. 5). The NA of lenses in projection aligner ranges between ~ 0.16 - 0.40 .

The resolution of a lens depends on the wavelength and the degree of coherence of the incident light, and the NA of the lens. The definition of resolution is based on *Rayleighs criterion*. That is, diffraction causes even a geometrically perfect lens to image an ideal infinitesimally small point source into a blurry disc, called the *airy disc*. When two points are so close that the two airy discs look like a single blurred disc, the two points cannot be resolved. Rayleighs criterion defines two images as being *just resolved* when the intensity between them drops to 80% of the image intensity (Fig. 6). Mathematically, this criterion is expressed as³:

$$2b = 0.61 \lambda / NA \quad (3)$$

where: $2b$ is the separation distance of two images (i.e. as shown in Fig. 8b, it is the sum of the dimensions of a line and a space on a wafer, each of dimension b); and λ is the illuminating wavelength. Figure 7 plots the Rayleigh limit (on the right of the plot) for lenses of various NA (on left of the plot), when the illuminating wavelength is $\lambda = 436$ nm (i.e. the G-line of the mercury-arc spectrum, which is a widely utilized exposure wavelength in many aligners)⁴. For the Zeiss 10-77-82, which has an NA of 0.28, and is a lens used in several projection stepper aligners, the Rayleigh limit of the minimum resolvable dimension, b , is shown to be $0.47 \mu\text{m}$.

Because the image is constructed from diffracted light, and the collection of higher orders of

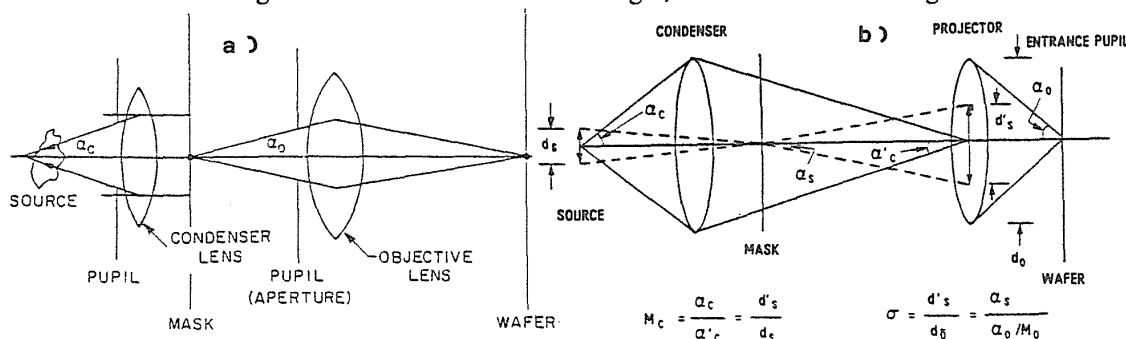


Fig. 5 (a) A refractive lens imaging system using partially coherent light, condenser lens, and objective lens. (b) Kohler illumination system. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

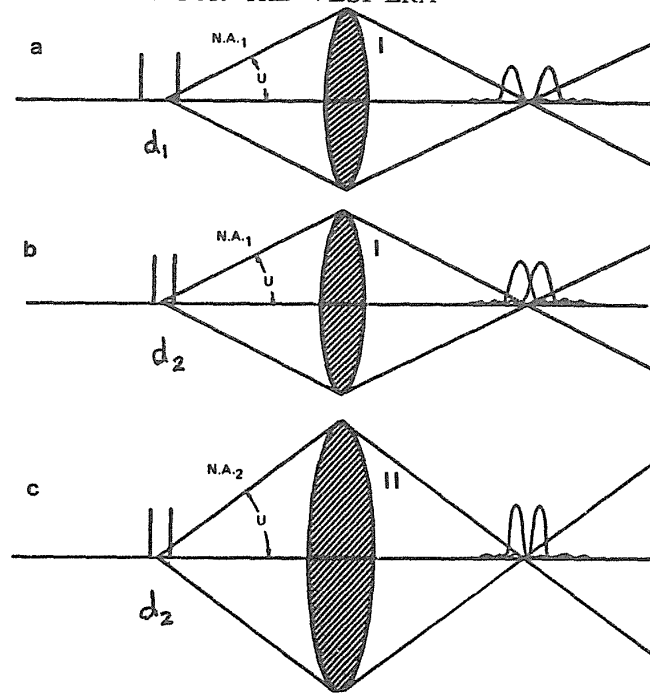


Fig. 6 Example of Rayleigh criterion. (a) Example lens I with $NA = 0.1$ can resolve objects separated by distance d_1 . (b) Example lens I cannot resolve objects separated by distance $d_2 < d_1$. Image intensities are shown on right of lens. (c) Example lens II with larger NA (e.g. $NA = 0.2$) can resolve two objects at a distance smaller than the resolution limit of lens I (e.g. $d_2 < d_1$).

diffracted light enhances the resolution of the image, a larger NA would allow a larger angle of collection, and therefore better resolution (also seen in Figs. 6 and 7). This benefit, however, also has a price, in that the depth of focus, σ , is inversely proportional to the square of the NA, or:

$$\sigma = \lambda / (NA)^2 \quad (4)$$

For example, for an $NA = 0.3$ and a $\lambda = 0.4 \mu\text{m}$, $\sigma = 4.4 \mu\text{m}$. From this example, it can be readily seen that variations in silicon substrate flatness could easily render an image outside the

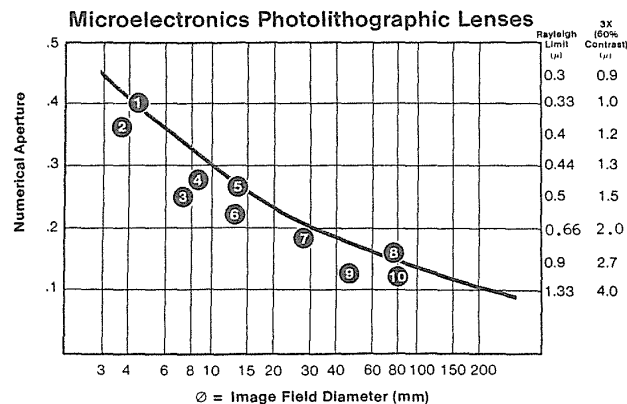


Fig. 7 The relationship between the NA and the effective field size of commercially available (1980) microelectronic photolithographic lenses¹³. Reprinted with permission of SPIE.

focal plane. Therefore, an appropriate compromise between high resolution and long depth of focus must be established in designing aligners. Nevertheless, it is predicted that at some dimension between 1 μm and 0.5 μm , the depth of field becomes intolerably small, and this will force optical lithography to give way to electron or x-ray lithography, as higher resolution is pursued. Others argue that use of planarization techniques, and shorter wavelengths (e.g. I-line), will be employed to combat the depth of focus limitation, allowing optical resolution to be extended.

As also shown in Fig. 7, for refractive-type projection printing systems (defined in a later section), higher NA achieves greater resolution at the expense of another property, that of *image field size*. Since image field size decreases significantly (e.g. the largest image field size of lenses used in 5X reduction steppers is 20 mm x 20 mm), in order to print a pattern on a 100 mm or larger wafer, several consecutive exposures must be conducted, using a *step-and-repeat* type exposure method.

Modulation Transfer Function

The *modulation transfer function*, or MTF, is a parameter which, when appropriately plotted, provides a rapid and convenient indication of the capability of an optical projection system to reproduce a mask image on a wafer surface^{1,5}. This system imaging capability depends on several parameters, including the illuminating wavelength, the mask feature size being imaged, the NA of the lens, and spatial coherence of the source. A clear understanding of the MTF concept is essential for appreciating the tradeoffs between various projection aligner systems. To begin our explanation of this parameter, we define the concept of modulation, M , as it applies to incident light energy on a plane:

$$M = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \quad (5)$$

where $I_{\max}$ is the image intensity at the center of a bright area, and $I_{\min}$ is the intensity at the center of a dark pattern. As shown in Fig. 8, knowledge of M reveals the degree to which diffraction effects cause incident radiation to fall between the images on a screen of two slits in the mask. If $M = 1$, $I_{\min} = 0$, and this is the highest degree of modulation that can be achieved. In Fig. 8 the modulation can be determined both at the object plane (i.e. the plane of the mask), M_{mask} , and at the image plane, M_{im} . The MTF of an exposure system is then defined as the ratio of the modulation in the image plane to that in the object plane, or $M_{\text{im}}/M_{\text{mask}}$. Note that having said this, since the intensity of the light in the mask plane at the center of an opaque line on the mask is essentially zero, $M_{\text{mask}} = 1$, and we can simply consider the MTF and M_{im} as identical. Making note of this simplification makes the concept of MTF easier to describe.

As stated at the outset, MTF depends on the NA, on λ , on mask feature size, and on the degree of spatial coherency of the illuminating system. Since λ and the NA of the lens are typically fixed by system hardware design considerations, it is most useful to plot MTF versus feature size and parametrically vary the spatial coherency. (Actually as shown in Fig. 8, MTF is plotted versus line pairs per mm, v , which can be converted to feature size, b , by $b [\mu\text{m}] = 1/2v$.) Let us study the plot in more detail, with the assumption that $M_{\text{mask}} = 1$.

At the extreme limit of the optical system resolution (i.e. the minimum distance that satisfies Rayleigh's criterion), given by point A in Fig. 9a the MTF is ~ 0.1 . As the size of the images to be printed becomes larger, however, the value of MTF increases. The maximum value of the MTF function is 1 (point C in Fig. 9), corresponding to a condition at which some point of the space between two images on the image plane receives no light (Fig. 8c). Under such

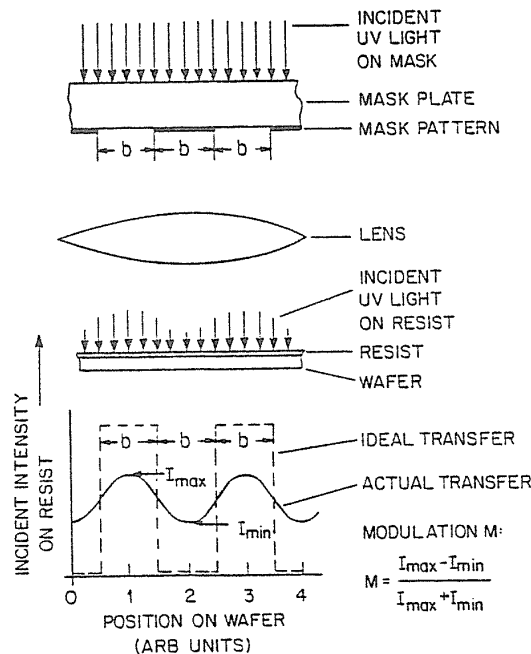


Fig. 8 Schematic representation of image transfer efficiency for a 1:1 projection printer. Reprinted with permission of the publisher, the Electrochemical Society.

conditions, two images incident on photoresist could certainly be printed as two distinct features. To summarize, the MTF curves shown in Fig. 9 describe the degree of modulation produced by a given optical projection system on a wafer surface, for different feature sizes on a mask.

Wafer surfaces are coated with a photoresist designed to respond to the incident radiation, and the relevant response characteristic for this discussion is the *resist contrast*, as defined in Chap. 12. An ideal resist would have an infinite contrast, and in such ideal material image dimensions equal or greater than the Rayleigh limit of the optical system could be printed. *Real resists, however, have finite contrast values, and thus a greater degree of modulation (MTF) than occurs at the Rayleigh limit must exist before an adequate image can be formed in a real resist.* The minimum MTF of an optical system to adequately define an image in a resist depends on the resist contrast value, and is defined as the *critical MTF*, or $CMTF_{resist}$ ⁶. Figure 5 in Chap. 12 is a plot of $CMTF_{resist}$ versus resist contrast. For example, the contrast of positive optical resists is ~ 2 , and from Fig. 5, Chap. 12, it is seen that $CMTF_{resist}$ when using positive resist is ~ 0.6 . Examining Fig. 9, this implies that in a system with an NA of 0.3, a λ of 436 nm, and a spatial coherency of 0.7, the maximum spatial grating frequency that can be printed on a film of positive optical photoresist is 442 line pairs/mm, corresponding to a minimum feature size of 1.13 μm (point B in Fig. 9). This example demonstrates the *2.5x rule of thumb*, which relates the minimum resolution of a projection aligner given by the Rayleigh limit and the actual working resolution achievable with positive optical resist⁴.

The fabrication of increasingly smaller features on VLSI relies on the availability of increasingly higher resolution lithography equipment. From the discussion on MTF, the approaches used to design such equipment can now be described. First, referring back to the Rayleigh criterion, the illuminating wavelength can be decreased, or the NA of the system lens can be increased. Second, the contrast of the resist can be increased, by modifying the resist chemistry, by creating entirely new resists, or by using contrast enhancement layers, which

allows a smaller MTF to produce adequate images. Third, the coherence of the optical system can be adjusted. Let us close the discussion on MTF with a brief description on this last subject.

Varying the spatial coherence alters the shape of the MTF curve^{5,12}. *Completely coherent radiation* ($s = 0$), yields an MTF curve as shown in Fig. 9. *Completely incoherent radiation* ($s = \infty$) produces an MTF curve that has a greater Rayleigh resolution limit, but whose MTF value increases only slowly as the feature size increases. *Partially coherent radiation* yields MTF curves in-between these two extremes, resulting in a higher MTF at a given spatial frequency than if completely incoherent radiation is used. Use of partially coherent radiation is also more advantageous than highly coherent radiation for two other reasons: 1) radiation with coherence values $s < 0.4$ produces an MTF of higher value at a given spatial frequency, but such coherence is achieved by reducing the effective source size (thereby increasing exposure time); and 2) such highly coherent radiation degrades the edge integrity of isolated edges by a phenomenon known as *ringing* (Fig. 10). Based on various tradeoffs, a coherence value of ~ 0.7 is typically selected for reduction steppers and ~ 0.45 is used for 1X steppers.

The configuration used in many refractive projection systems is a Kohler illumination system, in which the exposure source is imaged through a condenser in the entrance pupil of the

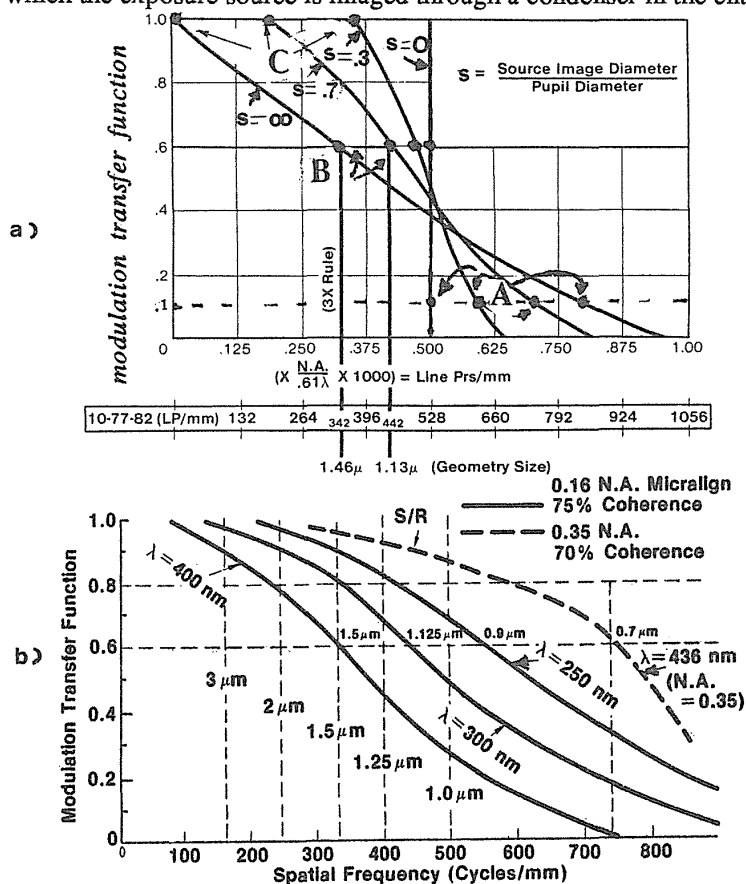


Fig. 9 (a) The modulation transfer function for a projection system with $NA = 0.28$, $\lambda = 436$ nm and three coherence factors⁴. Reprinted with permission of SPIE. (b) Modulation transfer functions for scanning projection aligner with $NA = 0.16$ (exposure wavelengths 250 nm, 300 nm, and 400 nm), and S/R aligner with $NA = 0.35$ (exposure wavelength 436 nm)¹⁸. Reprinted by permission of Solid State Technology, published by Technical Publishing, a company of Dun & Bradstreet.

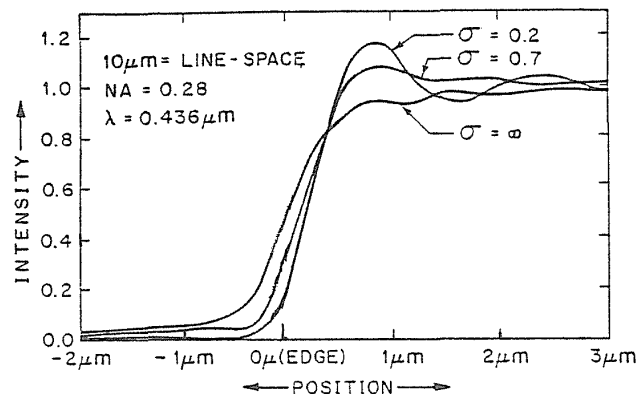


Fig. 10 Image intensity profile at the edge of an opaque line in a grating of 10 μm lines and spaces, showing effect of coherency on ringing. Reprinted with permission of Ref. 1. Copyright 1983, American Chemical Society.

projection lens, Fig. 5b. The degree of spatial coherence, s , in such systems is given by:

$$s = d_s / d_o \quad (6)$$

where d_s is the effective size of the source imaged by the condenser lens, and d_o is the diameter of the entrance pupil which is determined either by the diameter of the projection lens or a stopped-down aperture. In general, the distances are chosen to keep the source size less than the entrance pupil to produce the desired partial coherence value as described above.

OPTICAL METHODS OF TRANSFERRING PATTERNS TO A WAFER: OPTICAL ALIGNERS

The optical theory presented in earlier sections is applied to the design of the machines used to image the circuit patterns onto the resist-coated wafers. Such machines contain a variety of subsystems that work together to perform the imaging function, including: a) an illumination source that provides the optical energy for transforming the photoresist; b) an optical subsystem that focuses the circuit patterns onto the wafer surface and allows for controlled exposure times; c) a movable stage that holds the wafer to be exposed. The stage position can be finely and accurately adjusted so that the image from the optical pattern transfer tool (i.e. the reticle or mask) can be aligned to previously printed patterns on the wafer. This step, in fact is so critical, that the machines we are describing are most commonly referred to as *aligners*, as well as printers, exposure tools, etc.; d) some form of alignment subsystem (i.e. manual alignment, by a human operator using a microscope and manual mechanical adjustments, has been the traditional method used. Automatic alignment methods have been developed for wafer steppers, which require no human intervention); e) a wafer handling subsystem; and f) an exposure meter.

There are three major methods of optically transferring a pattern on a mask to a photoresist coated wafer^{7,8}. These are *contact printing*, *proximity printing*, and *projection printing* (Fig. 11). Projection printing is used almost exclusively for VLSI fabrication, and it is accomplished using three different types of projection aligning systems: 1) projection scanning systems; 2) reduction (e.g. by 10X or 5X) step-and-repeat projection systems; and 3) 1X step-and-repeat

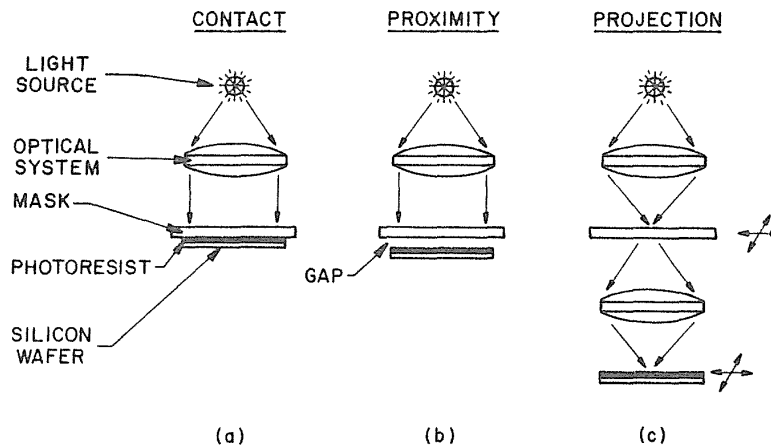


Fig. 11 Schematic of three optical lithographic techniques. (a) Contact. (b) Proximity. (c) Projection²⁷. Copyright 1983, Bell Telephone Laboratories, Incorporated, reprinted with permission.

projection systems^{9,10}. This section primarily describes projection aligners, and the advantages and limitations each type possesses. Light sources and exposure meters are discussed first.

A few words about the environment that is necessary for operating high performance aligners and for performing the majority of photoresist processing steps is in order. First, the light in the rooms needs to be filtered (i.e. yellow light) so that resist is minimally exposed when subjected to ambient light. Next the temperature in the photoresist processing and aligner rooms must be controlled to within $\pm 1^\circ\text{C}$, and the entire aligner apparatus itself must be kept at the same temperature. The room should be maintained to Class 10 cleanliness standards (see Vol. 2), and the humidity set at $\sim 50\%$ (and controlled to $\pm 5\%$ of the set point). The aligners must be highly isolated from vibration by use of vibration isolation tables, as well as through appropriate vibration-isolation building design practices.

Light Sources and Light Meters for Optical Aligners

Virtually all optical aligners used in IC fabrication utilize mercury-vapor lamps as the illumination source. In such lamps a discharge arc of the high-pressure (e.g. 230 atm) mercury vapor emits a characteristic spectrum. The mercury-vapor emission spectrum is shown in Fig. 12. It is not of uniform intensity at all wavelengths, and in fact contains several intense, sharp

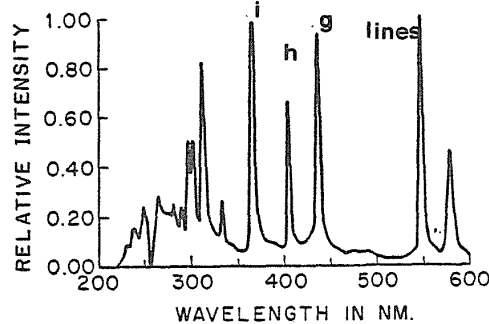


Fig. 12 Typical high pressure mercury-arc spectrum. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

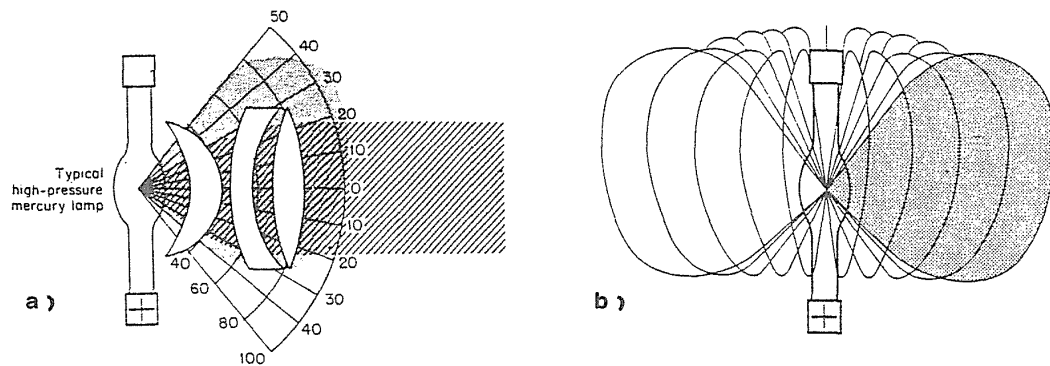


Fig. 13 (a) Schematic showing the relative intensity distribution with respect to the output of a mercury-arc lamp. (b) Three dimensional view of the output of a typical mercury-arc lamp. Reprinted with permission of SPIE⁴.

lines. In the UV wavelength range from 350 to 450 nm, there are three strong lines, the I-line (365 nm), the H-line (405 nm), and the G-line (436 nm). Most reduction steppers are designed to operate using the G-line (although development on I-line reduction steppers is being pursued¹¹). The 1X steppers utilize a wider portion of the spectrum than just a single line (i.e. the wavelength range between 390-450 nm). The 1:1 projection scanners are available in models that can operate at all three emission lines, as well as a deep-UV model that operates at 240 nm.

To obtain maximum intensity, high power mercury-arc lamps are used (e.g. 200-1000W). In some systems, air jets cool the bulb, and the heated air is removed by an exhaust fan. This is important because heat will not only cause shifts in the spectral output of the lamp, but can also cause dimensional changes in the mask and optical path length of projection aligners. The relative intensity distribution of the lamp in two dimensions is shown in Fig. 13a, and in three dimensions in Fig. 13b¹³. Collecting optics systems, which surround the lamp, are used to direct as much of the emitted light as possible to the surface being exposed. Filters are also used to limit exposure wavelengths to the specified frequencies and bandwidth.

The spectral output of the lamps vary with age, and together with variations in glass transmission and optical element coatings, exposure energy can change with time, or from machine-to-machine (even with the same lamp model). As a result, a spectral exposure meter must be used so that a correct and repeatable total energy dose is provided for each exposure. As

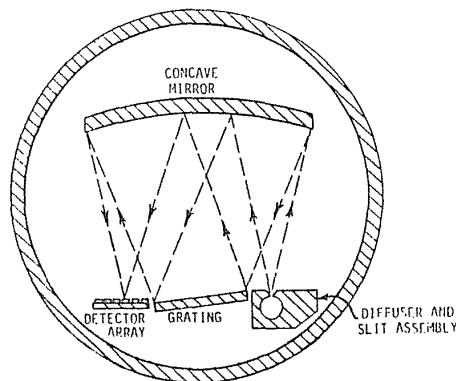


Fig. 14 Schematic of detection of a spectral exposure meter¹⁴. Reprinted by permission of SPIE.

the lamp output varies, the exposure time can be adjusted to maintain a constant incident energy dose onto each wafer. The meter must also be spectrally matched to the photoresist type being exposed. Typical exposure meters for these applications use filters to set their spectral response, but the limited variety of transmission curves available in filters results in a relatively crude approximation of the response of actual photoresists. More recently, exposure meters which contain a complete UV spectrometer have been developed (Fig. 14)¹⁴. They can be adjusted to match the response of any photoresist over the wavelength range from 254-436 nm.

Contact Printing

Contact printing was the earliest method used to produce patterns on silicon wafers^{8,15}. A schematic representation of a contact printer is shown in Fig. 11a. The mask containing the circuit pattern is first correctly positioned (aligned) relative to existing patterns on the wafer. Next, the mask is clamped to the resist-coated wafer (while maintaining alignment), and exposed with UV light. This form of printing yields the most faithful image transfer and best resolution.

Unfortunately, as a result of the repeated mask-to-wafer contacting process, defects in the mask are generated. These defects print on the next wafer that is exposed through the mask. To minimize this effect, hard surface masks must be inspected and cleaned regularly. If the defects cannot be removed by cleaning, the mask must be replaced. Particles between the mask and wafer also prevent intimate contact which reduces resolution in the local area. This has led to the virtual abandonment of contact printing for VLSI, and the development of techniques in which the wafer and mask do not make contact.

Proximity Printing

The next form of pattern transfer to evolve was *proximity printing*, in which the mask and wafer are placed close to one another during exposure, but do not make contact^{8,15}. By introducing such a gap between the mask and wafer, the defect problem of contact printing should be avoided. As the gap size is increased, however, the resolution rapidly degrades. For example, a 10 μm gap with 400 nm exposing radiation results in a minimum resolution of $W_{\min} = 3 \mu\text{m}$.

The use of this technique also requires extremely flat masks and wafers. In spite of the fact that many of today's wafers are flat enough to allow the use of a 10 μm gap, many VLSI circuits require features smaller than 2 μm . As a result, this technique is also not adequate for VLSI.

Projection Printing

In projection printing, lens elements or mirrors are used to focus the mask image on the wafer surface, which is separated from the mask by large distances. Several types of projection printing techniques have been developed, including: a) 1:1 projection scanners (based on reflective optics); b) reduction step-and-repeat projection aligners (based on refractive optics); and c) non-reduction (i.e. 1X) step-and-repeat projection aligners (based on a reflective /refractive system).

1:1 Scanning Projection Aligners

The 1:1 wafer scan system marketed by Perkin-Elmer (Micralign[®] series aligners), uses a reflective spherical mirror to project the image onto the wafer surface^{15,16,17}. Figure 15 shows a schematic diagram of such a system. It is seen that a narrow arc of radiation is imaged from the mask to the wafer, with the light traveling an optical path that reflects it 5 times, most importantly by a spherical mirror of NA = 0.16. The wafer and mask are scanned through this

arc of radiation by means of a continuous scanning mechanism. The scanning technique minimizes mirror distortions and aberrations by keeping the imaging illumination in the "sweet spot" of maximum optical correction. The image formed is a mirror image of the mask. These systems use Hg lamps with the range of 240 to 440 nm. A resolution of better than $1.50\ \mu\text{m}$ is reportedly attainable when 350-400 nm light is used. At deep UV (240 nm), exposure resolution close to $1\ \mu\text{m}$ can be achieved¹⁸. The depth of focus of the system is $\pm 6\ \mu\text{m}$, and overlay accuracy of $\pm 0.25\ \mu\text{m}$ (1σ) is possible. A throughput of 100, 150 mm wafers/hr can also be accomplished. In most applications, such scanning projection aligners are used to align patterns with minimum feature sizes of $\sim 3.0\ \mu\text{m}$, while step-and-repeat aligners (steppers) are utilized for smaller sized patterns. In processes that utilize some mask layers with minimum feature sizes of $\leq 3\ \mu\text{m}$, and others of $\geq 3\ \mu\text{m}$, both aligner types can be used in a *mix-and-match* approach, to take advantage of the high throughput of scanners¹⁹.

Reduction Step-and-Repeat Projection Aligners (Reduction Steppers)

The second type of projection exposure system uses *refractive*, instead of reflective, optics to project the mask image onto the wafer. It is impractically complex and expensive to produce a lens capable of projecting a mask over an entire 100 mm or larger wafer. Therefore, refractive systems are designed to project an image only onto a portion of the wafer. This field is then stepped-and-repeated (S/R) across the wafer, and aligners that operate in this manner are known as *steppers*. Wafer size is therefore no longer a limitation. Current systems employ reticles that have a pattern that is an enlargement of the desired image on the wafer. Thus, the reticle pattern is reduced when it is projected onto the wafer during exposure.

The ultimate advantage of stepper technology over scanner-type aligners is higher image resolution^{9,18}. In addition, stepping each die allows correction for wafer distortion. The necessity of conducting a step-and-repeat exposure reduces the throughput of these machines, but this approach also offers the possibility of outstanding overlay accuracy and resolution. Precise control of a mechanical stage is required to ensure accurate step and repeat exposures. Figure 16 shows a schematic of a step-and-repeat (S/R) reduction projection system.

Increasingly more attention is being given to lithography with wafer steppers near and below $1\ \mu\text{m}$. It was estimated in 1986 that $\sim 80\%$ of the installed steppers were being used to produce high-density memory chips, including 256K and 1M DRAMs, static CMOS RAMs, and EPROMs. The remainder are being used to develop new products, bipolar, and MOS logic⁹.

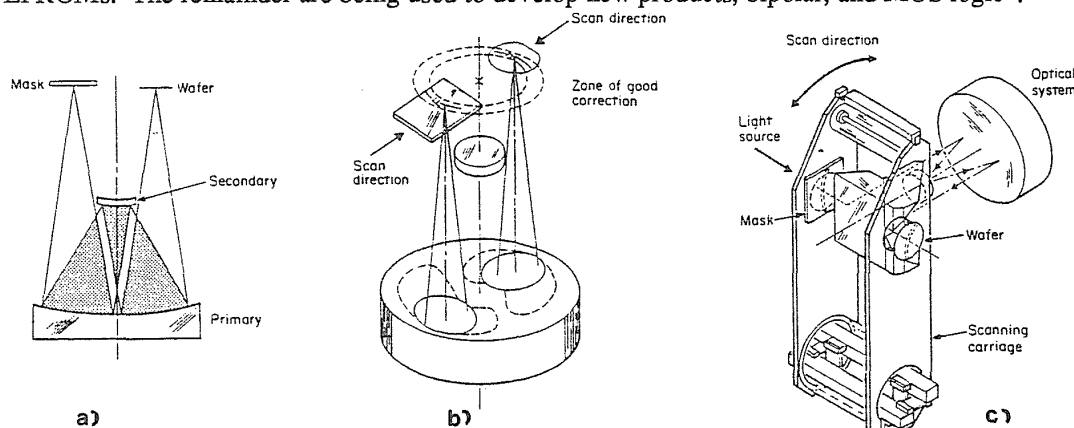


Fig. 15 Scanning projection optical system. (a) basic optical system consisting of two concentric spherical reflecting surfaces. (b) zone of good correction. (c) Micralign[®] projection and scanning system. Courtesy of Perkin-Elmer.

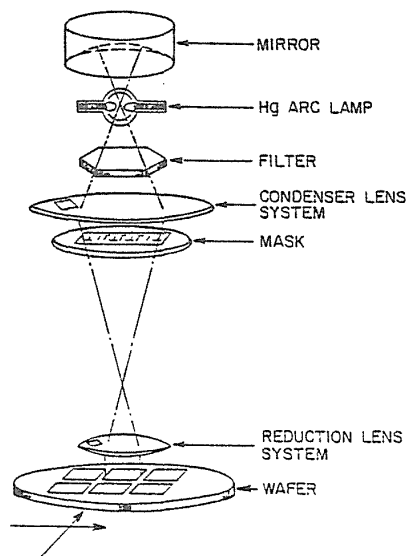


Fig. 16 Schematic of a reduction step-and-repeat system. Reprinted with permission of Ref. 1, Copyright 1983, American Chemical Society.

The first reduction steppers developed were 10X, but 5X steppers have largely replaced them. This has occurred primarily because of the greater utility of 5X reduction lithography^{9,20,23}. That is, a typical field size of a 5X lens projected onto a wafer is 14 mm x 14 mm. The size of this pattern at 5X is thus 70 mm x 70 mm, which can be accommodated on a standard 5" x 5" reticle substrate. The same field size at 10X becomes impractically large, requiring a 7" x 7" reticle substrate. 5X lenses also have larger field sizes (up to 20 mm x 20 mm, versus 10 mm x 10 mm for a 10X lens), which allows greater throughput.

Non-Reduction Step-and-Repeat Projection Aligners (1X Steppers)

A recently introduced system uses a 1:1 catadioptric optical system (i.e. a system consisting of a mirror, two folding prisms, and a two element achromatic lens), rather than a reduction lens (Ultratech 1000, Fig. 17). The principal optical element is a mirror (NA = 0.315), but apart from the combination mirror /lens, the system operates in a conventional step-and-repeat mode^{21,22}. Since the optical effects of defects cannot be decreased by reduction, as in 10X and 5X steppers, 1X reticles must be defect-free. Once a defect-free mask is fabricated, a protective pellicle (described in later sections) must be applied to it. The lens offers a larger field in one dimension than conventional refractive S/R lenses, thereby allowing more than one pattern to be printed at each exposure. When operated in the 390-450 nm wavelength range, the system achieves a working resolution of $\sim 1.0 \mu\text{m}$, an overlay accuracy budget of $\pm 0.25 \mu\text{m}$, and a depth of field of $5.0 \mu\text{m}$. If suitably adapted for deep-UV illumination, it could possibly offer $\sim 0.5 \mu\text{m}$ resolution. Registration (next section) is performed by an automatic local alignment technique.

PATTERN REGISTRATION

Up to this point, we have emphasized the quality of the lithographic imagery. Of comparable importance is the accuracy with which an image can be positioned on the surface of a wafer. That is, integrated circuits are fabricated by patterning a sequence of masking layers, and



Fig. 17 1X Stepper. Courtesy of Ultratech Stepper.

the features on successive layers bear a spatial relationship to one another. Thus, as a part of the fabrication process, each level must be aligned to the previous levels. Figure 18 is an example where a device feature on *masking level 2* is designed to be positioned within a feature on *masking level 1*, with the restriction that the edges of the *level 1* feature can never touch the edge of the feature on *level 2*. To insure that such edge overlap will not occur, a minimum *registration* or *overlay* tolerance must be allowed between the edges of level 1 and level 2. This tolerance then becomes one of the design rules used when laying out the circuit patterns.

Three factors contribute to the the magnitude of registration tolerance, and the effects of these factors must be considered together when establishing registration tolerance value:

- 1) The location of a feature edge on a silicon wafer may not be exactly at the location specified in the original circuit layout. The uncertainty in edge location can be

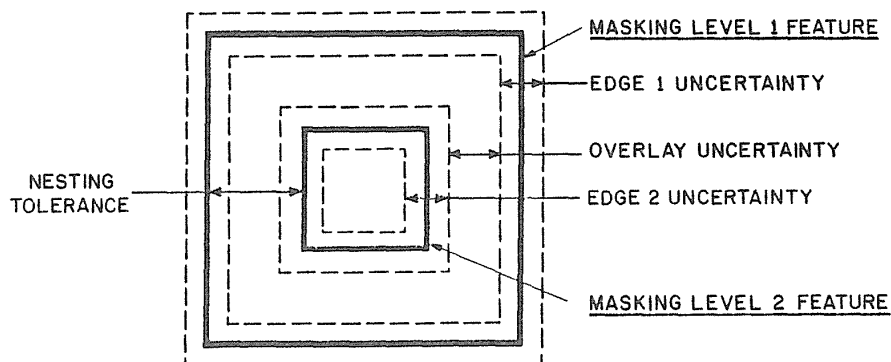


Fig. 18 Components of the nesting tolerance required between two mask levels registered to one another²⁷. Copyright 1983, Bell Telephone Laboratories, Incorporated, reprinted by permission.

due to the fact that: a) there is typically a measurable variation in line sizes across a mask, although such variation may be insignificant on reticles used with reduction steppers; b) the resist image on wafers can vary, because of non-uniformities in such parameters as resist thickness, baking temperature, exposure, and development; and c) non-uniformities in etching processes can lead to size variations in the etched features.

2) Dopants in the silicon substrate can diffuse laterally during processing, and the edge of a diffused layer may therefore not be coincident with the drawn edge location.

3) There is an uncertainty in *registering*, or *aligning* the image of level 2 to the previously etched pattern of level 1. This inability to perfectly align two layers may be due to several factors, including: a) the mask-making equipment may not produce a set of masks that perfectly overlay; b) temperature differences between times of exposure may cause relative mask expansion (or contraction), so that even a perfectly manufactured mask set may not produce perfect alignment; and c) the alignment tool has a limited registration capability. *In fact, from the standpoint of aligner fabrication capability, its overlay accuracy and machine-to-machine repeatability, and not linewidth control, commonly becomes its limiting characteristic.*⁵

To determine the magnitude of the registration tolerance that must be allowed between two mask levels, the distributions of the edge locations arising from all of the process parameter variations for *each of the two edges*, σ_{p1} and σ_{p2} , must be estimated, as well as the distributions of the edge locations due to registration variations, σ_r (we ignore the edge shift due to lateral diffusion in this discussion). Assuming that σ_{p1} , σ_{p2} , and σ_r are independent random variables with normal distributions (see Chap. 18), the probability that edges from level 1 and 2 will touch can be estimated for various registration tolerance values. The magnitude of the dimension, T , that will ensure that the probability of the two edges touching is only 0.1%, is given by²⁷:

$$T = 3 \left[\left(\frac{\sigma_{p1}}{2} \right)^2 + \left(\frac{\sigma_{p2}}{2} \right)^2 + \sigma_r^2 \right]^{1/2} \quad (7)$$

Typical values of σ_{p1} and σ_{p2} are $\pm 0.15 \mu\text{m}$ in a well controlled VLSI process line, and σ_r depends on factors as described above. Assuming a value of σ_r of $\pm 0.15 \mu\text{m}$, Eq. 7 predicts that a registration tolerance of $\approx 0.6 \mu\text{m}$ must be allowed.

Alignment of one pattern layer to previous layers is done with the assistance of special alignment patterns designed onto each mask level. When these special patterns are aligned, it is assumed that the remainder of the circuit patterns are also correctly aligned. The adjustment of the image of the mask being exposed to the previously produced patterns was originally performed by human operators, who compared the image locations under a microscope and adjusted the position of the mask to bring it into alignment with wafer patterns. Decreasing feature sizes, and the increasing number of alignments per wafer with steppers, have been the impetus for developing automatic alignment systems^{24,26} for use with projection aligners.

The principle of one type of automatic alignment procedure is illustrated in Fig. 19²⁵. Alignment marks consisting of two rectangular patterns, each set at a 45° angle to the directions of the stage motion are fabricated on the wafer (the black rectangles in Fig. 19). Two corresponding rectangular patterns are located on the reticle, and their image is projected onto the wafer (the larger clear rectangles in the figure). The superimposed alignment target and the reticle image are reflected back into the main optical element of the aligner, and then into an on-axis microscope. The image from the microscope is focused onto the face of a TV camera, and is subsequently digitized into a form that can be analyzed by a computer. When alignment is achieved, a signal as shown in Fig. 19 is obtained. The 45° orientation of the alignment marks makes it possible to obtain both x and y registration information from the horizontal

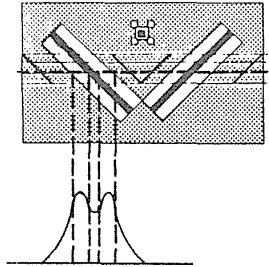


Fig. 19 Target for automatic alignment. Reprinted with permission of Microelectronics Manufacturing and Testing.

scan-lines of the video camera. The relative position of the wafer marks with respect to the reticle windows determines the registration of the two images.

Alignment in wafer steppers can be performed *globally* and *locally*. *Global alignment* performs rotational and translational alignment of the entire wafer. *Local alignment* provides alignment to a target within the particular die which is in position for immediate exposure, and is also referred to as *through the lens, site-by-site, die-by-die, or field-by-field alignment*. Global alignment is usually done at a remote alignment station before a wafer is sent under the projection lens for exposure, and is often used as the sole alignment in cases where the overlay tolerance is $> 0.7 \mu\text{m}$. Substantial time is saved by performing only a single global alignment, and hence exposure throughput can be significantly increased²⁴. In such cases, following global alignment, the wafer is moved to each step-and-repeat site by *dead reckoning*, and then each site is exposed. Such an exposure procedure is also referred to as *blind stepping*. When local alignment is used, a global alignment always precedes the sequence of local alignments.

MASK and RETICLE FABRICATION

The pattern "tools" utilized in IC processing are known as reticles and masks. We define a *reticle* to be a tool containing a pattern image that must be stepped and repeated in order to expose an entire substrate. Usually the pattern size is enlarged from 2X to 20X the size of the image on the substrate, but in some instances is of equal size. A *mask* is defined as a pattern tool which contains patterns that can be transferred to an *entire wafer (or to another mask) in one exposure*. Reticles are used in two applications: 1) for printing images of patterns onto masks; and 2) for printing images directly onto wafers in step-and-repeat aligners. In 1X wafer steppers, the pattern on the reticle is the same size as the image projected on the wafer, while the patterns on reticles of reduction steppers, consist of enlarged versions of the actual device patterns.

Figure 20 shows the various steps that can be utilized to transfer the circuit pattern data, as entered into a computer by the designer, to the wafer. For VLSI, e-beam writing on a 10X or 5X reticle, or direct e-beam generation of 1X masks, is becoming predominant²³, although optical pattern generation of reticles, and reduction-camera step-and-repeat of masks is still widely practiced. In this section the steps necessary to generate high quality masks and reticles are described. Such pattern tools must provide high resolution, low defect levels, and be optically compatible with exposure equipment, resists, and cleaning and etching processes. One pattern tool term worth defining at this point is its *polarity*. That is, a mask or reticle is said to be a *dark-field* (or *negative*) tool, if the field (or background) areas are opaque, and to be a *clear-field* (or *positive*) tool if the field is transparent (Fig. 21).

Glass Quality and Preparation

The glass used for photomasks and reticles must be free of defects on both surfaces, as well as internally, and should have high optical transmission at the resist exposure wavelength. Several types of glasses have been used for making photomasks, including: a) soda-lime glass; b) borosilicate glass; and c) quartz²⁸. *Green soda-lime glass* and *low sodium white soda-lime glass* (~50% more expensive) are easy to draw into large flat sheets and have shown excellent quality. Their high thermal expansion coefficient ($93 \times 10^{-7} \text{ cm/cm}^\circ\text{C}$), however, has made them largely unsuitable for projection applications. In applications where low expansion is required *borosilicate glasses* and *quartz*, with their lower thermal expansion coefficients

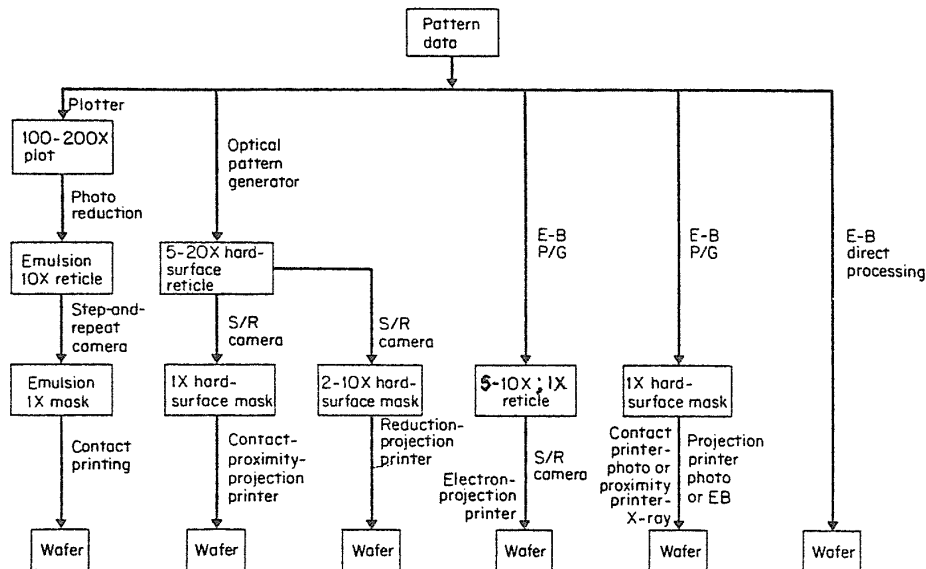


Fig. 20 Mask paths from design to wafer.

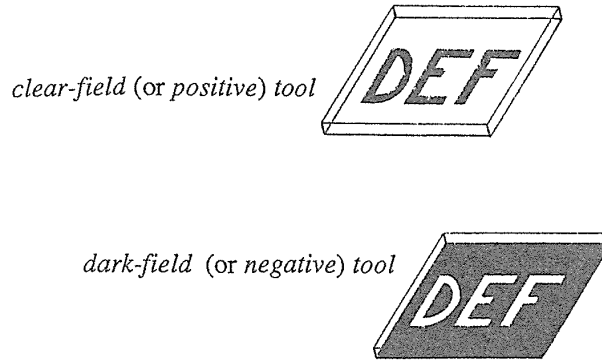
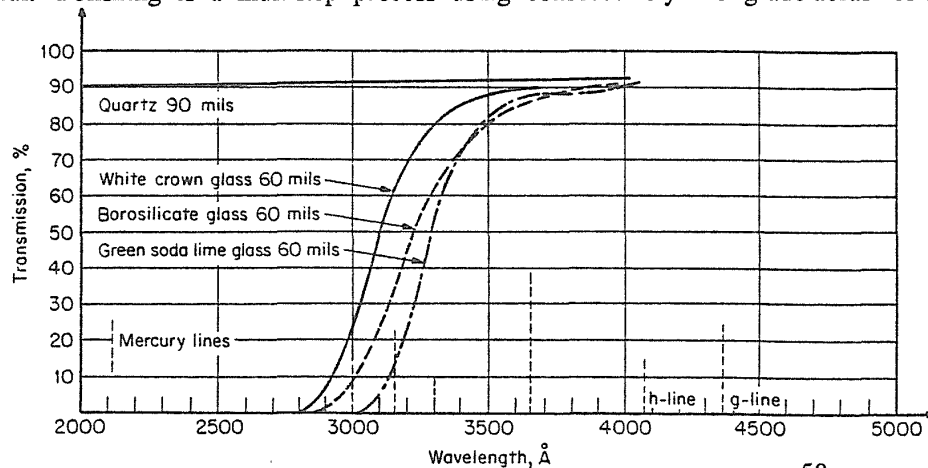


Fig. 21 Photomask polarity.

(37 and 5×10^{-7} cm/cm°C, respectively), have become the materials of choice. This is generally the case for projection printing where ambient temperature changes can result in dimensional and positional errors of the image on the wafer (run-out). *Quartz plates* are classified as ultra low expansion glasses, and result in very small amounts of thermal run-out. Quartz also has very high transmission in the near and deep-UV. Quartz, is more expensive, although it has recently become more affordable with the development of high quality synthetic quartz material²⁹. Natural quartz is manufactured by the Verneuil method, in which rock crystal is fused with oxygen and hydrogen gases. Synthetic quartz uses ultrapure silicon tetrachloride (SiCl_4). It offers a wider range of light transmission, a lower level of impurities and fewer physical defects. Its use is increasing with the number of applications that call for low run-out or deep UV. Figure 22 shows the transmission characteristics of various glasses used for masks.

The glass is prepared by cutting from large sheets. The inclusion-free plates are cleaned to remove chips, and then graded for flatness. Since non-flat masks can result in run-out, the grading specifies their run-out over the usable area of the mask. For step and repeat applications the flatness is somewhat less critical. Plates can also sag significantly under their own weight. Thus minimum plate thicknesses are recommended for each particular mask size. For example, a plate 5" x 5" should be 90 mils thick, while a 6" x 6" plate must be 120 mils thick.

The plates are then polished, cleaned, and inspected before coating with the mask forming material. Polishing is a multistep process using consecutively finer grade abrasives on both

Fig. 22 Transmission versus wavelength of different glass substrate materials⁵⁰.

sides of the plate. Plates are cleaned, rinsed, and dried prior to inspection and coating.

Glass Coating (Chrome)

The glass plates are next coated with a material in which the pattern is eventually formed. These materials include emulsion, chrome, and iron oxide. Emulsion is not used in VLSI because of its poor linewidth control, and its inability to stand up to use and cleaning. Chromium (chrome) is the most widely used material, and it is deposited onto the plate by sputtering or evaporation. Generally, the thickness is less than $1000\text{\AA}$. Sputtering has the advantage of high throughput, good adhesion, and excellent uniformity. It is possible to sputter etch the glass plate prior to the chrome deposition, resulting in improved adhesion. Vacuum deposition (e-beam evaporation) has also been used to prepare chrome plates in a vacuum of 10^{-5} - 10^{-6} torr. Although sputtered chrome can be more reflective than evaporated chrome (an undesirable property), use of anti-reflective coatings can overcome this drawback. Such coatings consist of a thin ($\sim 200\text{\AA}$) layer of Cr_2O_3 on the surface, which reduces the reflectivity. Figure 23 shows the reflectivity of chrome coatings as a function of wavelength, with and without anti-reflection coatings.

Mask Imaging (Resist Application and Processing)

The application of resist and its subsequent processing to produce images (either optically or by e-beam) is similar to that used for wafers (Chap. 12), except that the resist coating is much thinner, and different types of exposure equipment are used.

Prior to coating, the blanks are cleaned and dried, and then spin-coated with filtered photoresist. Such optical resists as AZ-1370 or Kodak 820, or e-beam resists as PMMA and COP (described in Chap. 14), are used for mask fabrication. Thick coatings ($\sim 0.5\text{ }\mu\text{m}$) result in improved line size control and pinhole protection, while thinner resists (0.2 - $0.3\text{ }\mu\text{m}$) result in better resolution.

The resist is soft-baked rapidly because of the thin coatings used. Exposure control is critical since the high reflectance chrome surface results in standing waves. Exposure of the resist can be performed either by an optical or e-beam method.

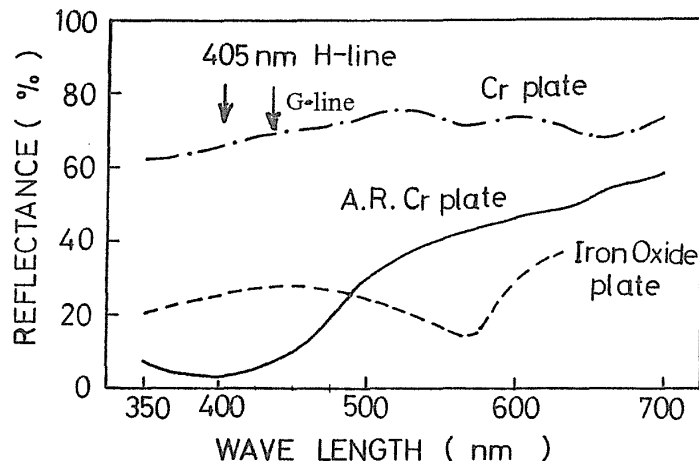


Fig. 23 Reflectance of chrome and anti-reflective chrome films used to produce reticles and masks.

Table 1. SELECTED WET ETCHANTS FOR CHROME FILMS

Alkaline Etch:	50g NaOH,	1 part	Ceric Ammonium Nitrate:	310g $\text{Ce}(\text{NH}_4)_2(\text{NO}_3)_6$ 120 ml HNO_3 (conc.) 1970 ml H_2O
	100 ml H_2O 100 g $\text{K}_3(\text{Fe}(\text{CN})_6)$ 300 mL H_2O	3 parts	Ceric Sulfate:	9 parts saturated $\text{Ce}(\text{SO}_4)_2$ (solution) 1 part HNO_3 (conc)

The resist is developed, typically with spray techniques. Tight control of developer concentration and temperature is critical for maintaining line size control. After this step, critical dimension (CD) and resolution measurements are made to insure they are in specification, and placement error is checked with a mask pattern or on a Nikon 2I[®]. The resist is then hard-baked (to ~100°C) prior to etching.

The pattern transfer into the chrome has largely been accomplished using wet etching, since the thin chrome films can be effectively wet-etched. Some etchants used are listed in Table 1.

There have been reports in the literature describing the plasma etching of chrome photomasks using CCl_4 , Cl_2 ³⁰, or CF_4 ³¹, all with O_2 . In order to form volatile compounds, a large proportion of oxygen must be used, but this results in resist erosion. Good selectivity between Cr and resist can be achieved at a pressure of 250 mtorr, a power of 35 watts, and a CCl_4/O_2 ratio of approximately 1.6. The maximum selectivity is about 1.5 at a chrome etch rate of 300 Å/min. Good selectivities can be obtained using e-beam resists such as PBS and COP. The sidewalls of the plasma etched features are sinusoidal in nature, but such structures do not cause a change in linewidth of the mask when viewed in projection.

It has also been reported that a reversal of resist tone (positive to negative) can be achieved by plasma processing³². Treatment of the exposed and developed resist pattern in a plasma (O_2 , SF_6 , or Ar) passivates the exposed chrome areas against wet etching. The resist is then stripped by conventional techniques, and the plate wet-etched. The unpassivated areas are attacked more rapidly by the etchant than the passivated areas. Black chrome (anti-reflective) passivates much better than shiny chrome. It is believed that the passivation results from material (SiO_2) sputtered from the backing plate.

Pattern Generation

Optical Pattern Generation of Reticles

During the previous decade, significant advances were made in the field of optical pattern generation (PG) for reticles³³. Patterns can be conveniently generated by imaging and exposing a set of accurately positioned rectangles onto the chrome plate. Since the patterns generated by integrated circuit designers are, in general, polygons, they must be decomposed into rectangles. This is termed "fracturing" the data. Figure 24 shows an example of a design shape fractured into its composite rectangles. The challenge of pattern generation is to reduce any image to a set of rectangles, each specified by a height and width, by x and y coordinates, and by an angle relative to the coordinate axes. Each rectangle can then be unambiguously defined with the following five coordinates: H , W , x , y , and θ .

The key components of the optical pattern generator (OPG) are apertures (or shutters), and a movable stage. The *shutters* are mounted on a movable head, which can also be rotated to give

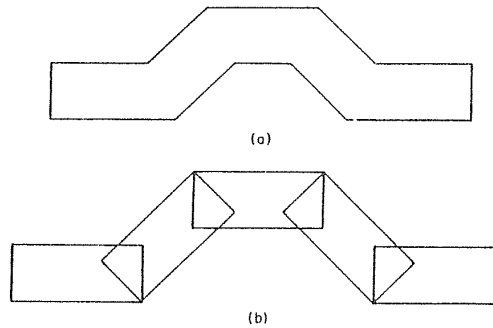


Fig. 24 (a) A polygon before fracturing into rectangles. (b) The fractured polygon¹⁵. Reprinted with permission of Academic Press.

desired values of θ , and the shutter size can be controlled to produce patterns with the specific rectangular dimensions, H and W . The rectangles are imaged through a 10X lens onto a photosensitive film that covers a chrome-coated glass plate. This plate is accurately positioned by a *laser controlled x-y stage*. The stage sets the center coordinates, x and y , of the rectangle defined by the apertures.

The variable aperture size can be controlled to within $\pm 7.5 \mu\text{m}$, which results in a $\pm 0.75 \mu\text{m}$ size uncertainty on a reticle (after a 10x reduction). This is the critical dimension (CD) control. If a 10X reticle is produced, a $\pm 0.075 \mu\text{m}$ error on a wafer results. Note that errors due to processing latitude both on the reticle and on the wafer occur in addition to the aperture size error. Position errors in x and y are quite small since the stage is under laser control. Stage control to the desired position, however, does result in positional errors. Such error can be traded off for throughput.

The throughput of an OPG depends on the complexity of the mask designs being generated, the optimization of the data fracturing program, and the positional accuracy required. A well tuned machine running an optimized pattern in AZ1370 has a throughput of 10,000 rectangle exposures (flashes) per hour. A complex VLSI circuit level may have in excess of 100,000 flashes, requiring more than 10 hours to produce a reticle. During this period temperature control better than $\pm 0.5^\circ\text{F}$ must be maintained so as not to result in additional positional errors. The quality of the reticle cannot be ascertained until after development and etch of the chrome. Flaws detected at that time may mean the scrapping of a 10 hour job. The low throughput along with reduced feature sizes, has made optical pattern generation of reticles much less attractive than electron beam generation for VLSI.

Directly-Stepped Photomasks

Photomasks for projection scanning aligners contain a large number of die patterns with the same dimensions as the patterns on the wafer^{33,34}. Such masks can be patterned by step-and-repeat the individual die patterns from a 10X reticle with a high-speed step-and-repeat camera. Two examples of such cameras are the GCA /MANN 3696 and the TRE / ELECTROMASK. The stepping motion of these cameras is metered with a He-Ne laser interferometer, and their stepping precision is $3\sigma \leq 0.25 \mu\text{m}$. The 10X reticle contains fiducial marks that align with the X and Y directions of the pattern on the reticle. When the reticle is mounted on the camera head, these fiducials are aligned to targets fixed to the head. The X and Y motions of the stage, on which the blank photomask plate is placed, are aligned to the camera head targets. The stage moves in the X and Y directions, precisely positioning the photomask plate prior to each

exposure of the die pattern. Step-and-repeat cameras can produce from ~0.5 to 15 plates per hour, depending on the plate size and the number of multiple patterns that must be stepped onto the plate (e.g. besides the circuit pattern, *test drop-in* patterns may be used).

Although the throughput of 10X step-and-repeat cameras can be high, they also have the following drawbacks: a) the maximum die size that can be printed is limited by the working diameter of the camera lens, to typically a 14-mm diagonal; b) the minimum resolution of the mask features is limited by the camera lens to ~1.0 μm ; and c) the best array registration is ~0.5 μm , compared to ~0.15 μm for e-beam pattern registration.

Electron Beam Pattern Generation

The electron beam exposure system (EBES) was originally developed at Bell Laboratories during the 1970s. It utilizes raster scan techniques to write the pattern. Commercial versions for mask fabrication are available and find wide use at both commercial and in-house mask shops. They are very well suited for 10X, 5X, and 1X reticle fabrication and also for 1X masters^{23,24}.

Figure 25 shows a schematic of the e-beam stage of such a system. A sensitized (e-beam resist) chrome plate is placed on the table and moved uniformly in X direction under the beam. The width of the scan is one beam diameter, and the scans are contiguous on the plate. A rectangle of 512 address units (AU) in height and 32,768 AU in length is contained in memory and is called a "stripe". The pattern is constructed of these stripes. How well these strips abut (as well as their size uniformity), both contribute to the precision of the pattern. If the scan is parallel to the pattern edge, the edge will be smooth. If it is perpendicular, however, it will show roughness, that is dependent on the spot size. Nevertheless, such edge roughness is not a problem for 10X and 5X reticle fabrication. Roughness can also result when writing an angled line, and this is called the *raster effect*³⁵. The abutment of the stripes, and drift in the electron beam also result in CD errors. The stripe abutment error arises from the inability to exactly align the stage motion to the beam motions and is generally less than 0.125 μm . Electron beam

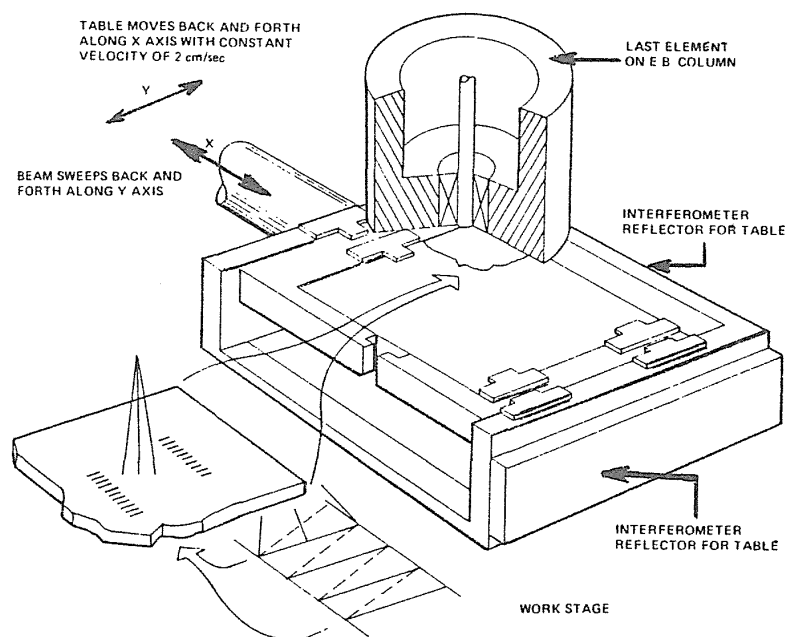


Fig. 25 The work stage of an e-beam system. The electron beam scans in the Y-axis as the stage traverses under the column in the X-axis. Courtesy of Perkin-Elmer - ETEC.

drift error is likewise quite small ($< 0.0625 \mu\text{m}$) in a five minute period. Variations in resist processing and exposure effects also add to the CD error. Consideration of all errors for a $1 \mu\text{m}$ spot (10X reticle) has a calculated RMS value of $0.27 \mu\text{m}$ if angled features are not written, and $1.04 \mu\text{m}$ if angled features are used. Again, for 10X and 5X reticles this presents no problem, but for 1X masters or reticles, a finer beam size ($0.25 \mu\text{m}$) must be used to reduce this error size.

Registration precision is the ability to *repeatably* place a feature at its site, while *registration accuracy* is the ability to place it where it is intended to go. In addition to abutment and beam drift, temperature variations during the reticle fabrication affect the placement of the feature. Values of registration accuracy of $0.3 \mu\text{m}$ have been achieved.

E-beam has an advantage over optical pattern generation in that uniform exposure is given to all rectangles of the pattern. Optical patterns, depending on the fracturing, can have areas that are double exposed (see Fig. 24)³⁶. Due to such additional exposure, the feature size can grow. The e-beam, on the other hand, turns on and off as required, thereby avoiding double exposure. As described in Chap. 14, however, for small features in dense patterns, the effect of back-scattering (leading to pattern distortion by proximity effects) must be accounted for in e-beam exposure. This is generally not a problem in 10X or even 5X reticles, but can be for 1X reticles.

A recently introduced potential alternative to e-beam pattern generation of reticles (at least for 5X and 10X reticles), is a laser-based system designed to produce reticles with a minimum feature size of $1.6 \mu\text{m}$, a CD uniformity of $\pm 0.12 \mu\text{m}$ and an overlay accuracy of $\pm 0.12 \mu\text{m}$, and a positioning accuracy of $\pm 0.25 \mu\text{m}$ over a field size of 128 mm^2 (e.g. the CORE 2000 by ATEQ³⁷). Such systems cost one-third as much as e-beam systems, are 5-10 times as fast, and use optical resists.

Mask and Reticle Defects and their Detection and Repair

Defects in masks and reticles have always been a source of yield reduction in integrated circuit manufacture. As the minimum pattern sizes approach $1 \mu\text{m}$ and below, and the circuits are designed with higher device densities, defects that were once tolerable can no longer be accepted. For example, a single defect that in the past killed only an individual die, now becomes a repeating defect in stepper systems, and will kill every die in single die reduction reticles. Such defects can be due to incorrect design of the mask patterns, or flaws introduced into the patterns during the pattern generation process. Even if the design is correct, and the pattern generation process is performed correctly, so that the desired mask patterns are produced, defects in the mask or reticle can be generated by the mask /reticle fabrication process, as well as during subsequent processing and handling.

It is true that reduction steppers do provide some reduction in the severity of such defect effects. That is, many defects are effectively rendered invisible by the simple expedient of a 10X reduction, and 5x steppers also enjoy this benefit, but to lesser extent. 1X systems, of course do not offer this opportunity for defect reduction, and reticles in such systems must therefore be prepared with greater care to avoid repeating defects, and are usually protected with pellicles (as described in a following section). 1X and 5X systems, however, may be able to place more than one die pattern on a reticle, and in such cases a defect will not kill every die.

It is the mask fabrication and wafer processing induced defects (and their repair), that are the subjects of this section. The detection of design or pattern generation flaws is discussed in a subsequent section on mask and reticle inspection. Figure 26 illustrates the types of defects that may be found on a mask as a result of mask fabrication and wafer fabrication problems. Defects which result in inoperative devices or which would cause a die to be rejected at final visual inspection are termed *fatal defects*, while others are nonfatal defects.

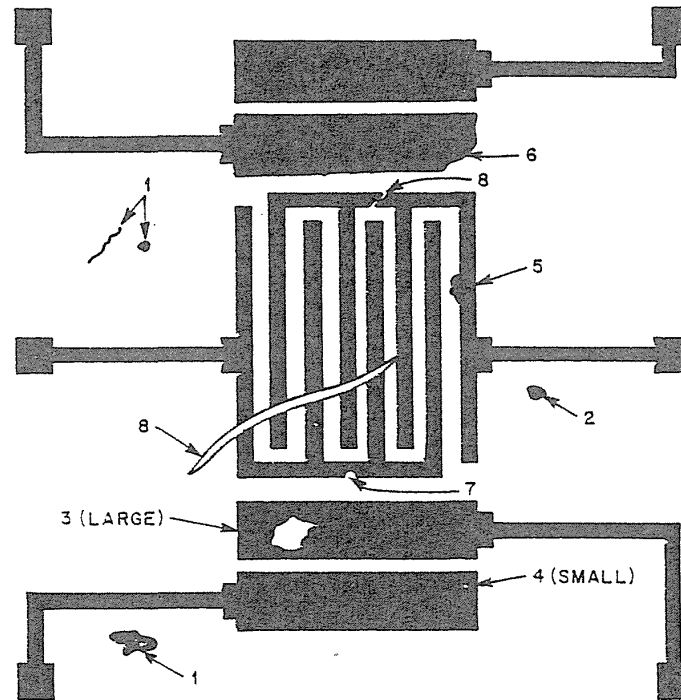


Fig. 26 Types of defects commonly encountered on a process line. (1) contamination, (b) opaque spot, (3) large hole, (4) pin hole, (5) excess material, (6) lack of adhesion, (7) intrusion (mouse nip) and (8) scratch. Reprinted by permission of Ref. 1, Copyright 1983, American Chemical Soc.

The causes of mask fabrication defects are first considered³⁸. *Raw glass substrates* can contain bubbles, scratches, pits and fractures. Bubbles are relatively rare in good quality plates and can be readily detected (and plates containing bubbles, rejected). Scratches, pits, and fractures are surface defects, which are harder to detect, and thus more likely to be found on a finished mask. Pits inhibit chrome adhesion, causing pinholes, while scratches produce nonuniform etching in local areas, especially at pattern edges. *Chrome defects* include: a) particulate inclusions in the film; b) pinholes or voids in the chrome surface; and c) invisible chemical anomalies (such as nitrides or carbides), which lead to erratic local etching that produces undesired patterns. *Resist defects* include voids, which produce pinholes (that lead to chrome spots), and resist gels that may locally affect resist solubility. Masks and reticles made with e-beam lithography require use of e-beam resists. Until recently, e-beam processing has been more prone to resist defects than conventional optical resist processing. Recent advances in e-beam resist and material technology have made them about equal. Of course *dirt particles* can also be introduced onto the mask plate during any of the pattern transfer steps, again leading to mask defects.

Upon completion of the mask or reticle fabrication sequence, a series of inspections to qualify the product are performed. The inspection procedure examines several characteristics of the mask or reticle, including: a) linewidth measurement; b) measurement of the registration among the arrayed die patterns (if more than a single die per mask or reticle is present); c) determining that all the features present in the design database have been transferred to the mask; and d) determining if any mask fabrication defects have been produced. Different inspection tools are utilized for each of the above inspections. Inspection procedures and tools for detecting fabrication defects are discussed in this section, while the other inspections are discussed later.

Mask fabrication defects are located by using transmitted light. In the past such inspections

were carried out by a human operator working with a microscope. As masks have become more complex, this task has been relegated to automatic defect detection systems that perform the task much more rapidly, and with fewer errors^{39,40}. These systems are also able to plot the distribution and size of defects over an entire mask. Defects (e.g. pinholes) as small as $0.35\ \mu\text{m}$ are detectable with $\sim 95\%$ probability on optically transparent substrates with the most recently designed systems. Since the detection of small defects by automatic systems is a probabilistic process, mask makers commonly run a reticle through an automatic system several times, to guarantee that all defects have been located.

Several automatic mask /reticle defect detection systems are being sold, including the KLA KLARIS³⁹, and the Cambridge Instrument's Chipcheck⁴¹. The most advanced models have the capability of performing both die-to-die and die-to-database inspection (Fig. 27). The *die-to-die* inspection allows defects unique to an individual die to be identified. *Die-to-database* inspection allows repeating defects to be found (which would not be detected by a die-to-die comparison), as well as errors made in converting data from the computer memory format to the mask /reticle pattern. With systems that can perform both such inspections, only one die of a mask array must be inspected against the database, while die-to-die inspection checks each die for random defects. A defect detection system based on holographic principles is also available⁴⁰. It is specified to detect particles $\geq 0.5\ \mu\text{m}$, and to be able to inspect masks with pellicles attached.

As a final check before going from reticle or mask to wafer, a glass wafer can be used⁴². With only a few die exposures on a glass wafer, an automatic reticle inspection system can qualify a reticle within minutes. Such glass wafers are dimensional replicas of standard silicon wafers offered in 76, 100, 125, and 150 mm sizes, and coated with a thin film of aluminum.

Repairing Defects in Masks and Reticles

Since fatal defects in a mask or reticle are obviously highly undesirable, or in cases of one die per reticle, entirely unacceptable, it would be useful if such defects could be repaired, thereby rendering the mask free of fatal defects. Mask repair methods for accomplishing this purpose

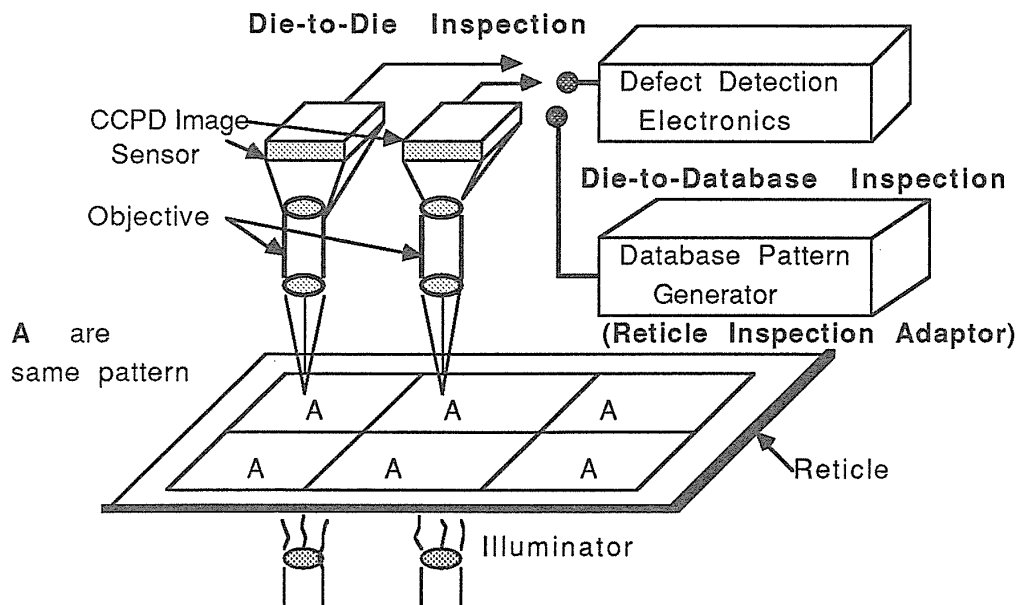


Fig. 27 Automatic defect detection instrument for masks and reticles. Courtesy of KLA Instruments Corp.

have been developed. The repair of *opaque defects* (i.e. removal of chromium spots from areas in which they do not belong) has been performed with lasers for many years (i.e. *laser zappers*). A focused laser beam merely evaporates unwanted material. One concern with laser evaporation is potential damage of the glass substrate. Large chrome spots may require several laser pulses to remove them, and if damage (*laser burn*) occurs, it can become another printable defect.

The repair of *clear defects* (i.e. the deposition of chromium in areas from which it should be missing) has proven more difficult. The most widely used process is a chromium lift-off procedure, which requires hours of processing time, and may introduce additional defects (Fig. 28a). As a result, several alternative methods have been developed. One uses a local pyrolytic decomposition of a chromium bearing-gas at the spot where the clear defect exists. The gas is delivered by a process-gas delivery needle into the space between a 100X microscope objective and the reticle surface. An argon laser beam is delivered through the microscope optics, and this beam increases the temperature of the desired spot ($\sim 1\text{ }\mu\text{m}$ in size) on the substrate surface to 150°C . This causes decomposition of the gas, and consequent local deposition of the chromium at the heated spot. Such deposited patches can be controlled in the $1\text{--}2\text{ }\mu\text{m}$ size range, and since they are composed of chrome, can be trimmed by a YAG laser to submicron dimensions for *mouse-nip* filling (Fig. 28b). Another method involves the application of epoxies (dispensed by pipette, while observing with a high-magnification, wide-field microscope). A third technique utilizes a focused ion beam to deposit chrome onto local regions of the substrate, or to locally etch a fine diffraction grating pattern onto the glass surface, so that it appears effectively opaque.

Pellicles

Even though masks and reticles used in projection printing can be fabricated without defects (i.e. by utilizing repair techniques if necessary), and no damage-creating contact between mask and wafer occurs, mask defects due to handling or airborne contamination can still be generated. In the regime of $\leq 1\text{ }\mu\text{m}$ resolution, particulates that are large enough to cause defects are also harder to detect and remove. Thus, even in projection printing processes, a method for

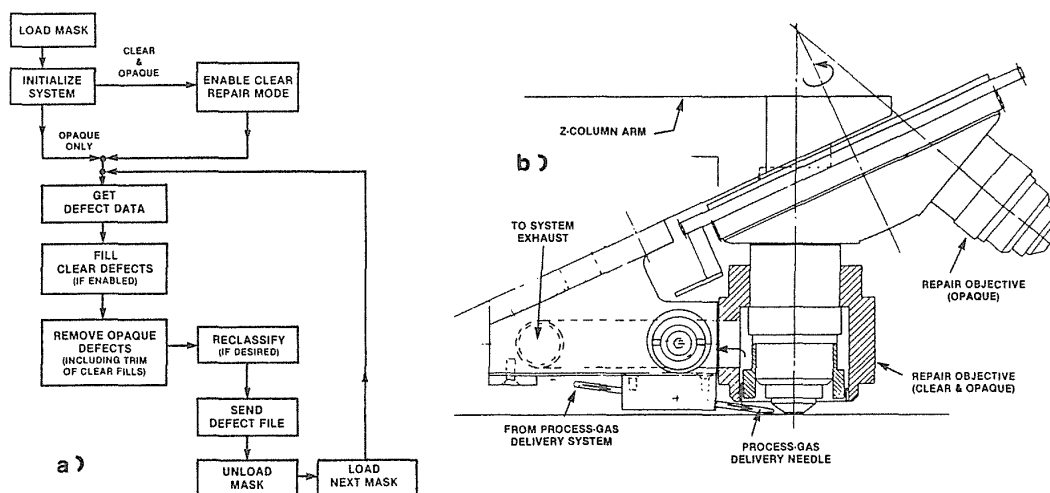


Fig. 28 (a) Typical photomask lift-off repair process cycle. (b) Opaque mask defect repair process by pyrolytic decomposition of chromium-bearing gas. Courtesy of Quantronix Corp.

protecting masks and reticles against such defects is highly desirable. Such a method is available, and it involves the use of pellicles^{44,45}.

A *pellicle* is a membrane that seals off the mask or reticle surface from airborne particulates and other forms of contamination. The membrane is mounted on a metal frame which is securely attached to the chrome side of the mask, as shown in Fig. 29a. Particles (typically <100 μm) which adhere to the pellicle surface are kept at a distance far enough from the wafer surface that they are not imaged onto the wafer surface (Fig. 29b). The membrane is thin enough to be optically transparent, strong enough to be stretched across a support ring that covers the entire printable area of a mask or reticle, and is sufficiently durable to withstand cleaning and handling. The membrane material must also be stable enough to retain its shape over long periods of time and exposure to 100,000 flashes of UV radiation, and be inexpensive enough to be cost effective. The pellicle material is usually nitrocellulose, with a thickness of 1-15 μm (typically ~2.9 μm).

Although it is easy to understand how a pellicle can prevent particles from directly contaminating the chrome surface of a mask, it is useful to elaborate upon the reason why particles which adhere to the pellicle surface may not be imaged onto the wafer surface. From Fig. 29 it can be seen that light directed at the wafer surface will be obscured by particles present both on the back side of the mask and the surface of the pellicle. To insure that a particle on either of these surfaces causes no more than a 10% reduction in the light intensity on the wafer surface, a minimum standoff distance from the mask for a given size of particle can be calculated. This standoff distance, D (in mm), for a particle size (in μm) is calculated from⁴⁴:

$$D = n F P / 280 \quad (8)$$

where n is the refractive index (1.0 for air, 1.5 for glass), and F is the condenser F-number at the mask or reticle ($F = 1 / \text{NA}$). Figure 29 gives some standoff distances versus particle size, for several values of F-number. For example, the $F/4$ curve is valid for the optical systems in the Perkin-Elmer 1:1 scanning aligner and the Ultratech Model 900 1:1 stepper. It shows that a mask plate thickness of 2.2 mm offers immunity against particles up to 50-100 μm , while a pellicle standoff distance of 2.5 mm provides excellent immunity against 100-200 μm particles. For 10:1 steppers, which have a greater depth of focus, a 2.2 mm plate only provides protection against 10 μm particles on the reticle backside. A second pellicle frequently attached to the reticle backside to provide double-sided protection. A study by Flamholz⁴⁶ indicates that because of their increased depth of focus, reduction-type steppers have their images impacted by particles at somewhat greater standoff distances than predicted by the simple model of Eq. 8. Furthermore, only limited protection is afforded against extended defects, such as hairs and fibers. Flamholz concluded that in order for pellicles to adequately provide protection in such systems, all pellicle parameters must be conservatively chosen (e.g. standoff distance, focus position).

The optical transmission losses of the pellicle material (due to reflection, absorption, and scattering) affects the exposure time, and thus throughput. (In the 350-450 nm range a 2.9 μm thick nitrocellulose pellicle, with an anti-reflection coating, has an average transmission of ~99%.) Nitrocellulose and mylar (another pellicle material), however, both exhibit strong absorption near 300 nm, which limits their usefulness for deep UV applications. Optical interference effects can also cause significant variations in transmission through a pellicle if the pellicle thickness exhibits even submicron nonuniformity. Fortunately, pellicles can be manufactured with thickness uniformities of better than 1%, minimizing such problems.

Masks or reticles with pellicles attached are cleaned with a DI water rinse to remove most

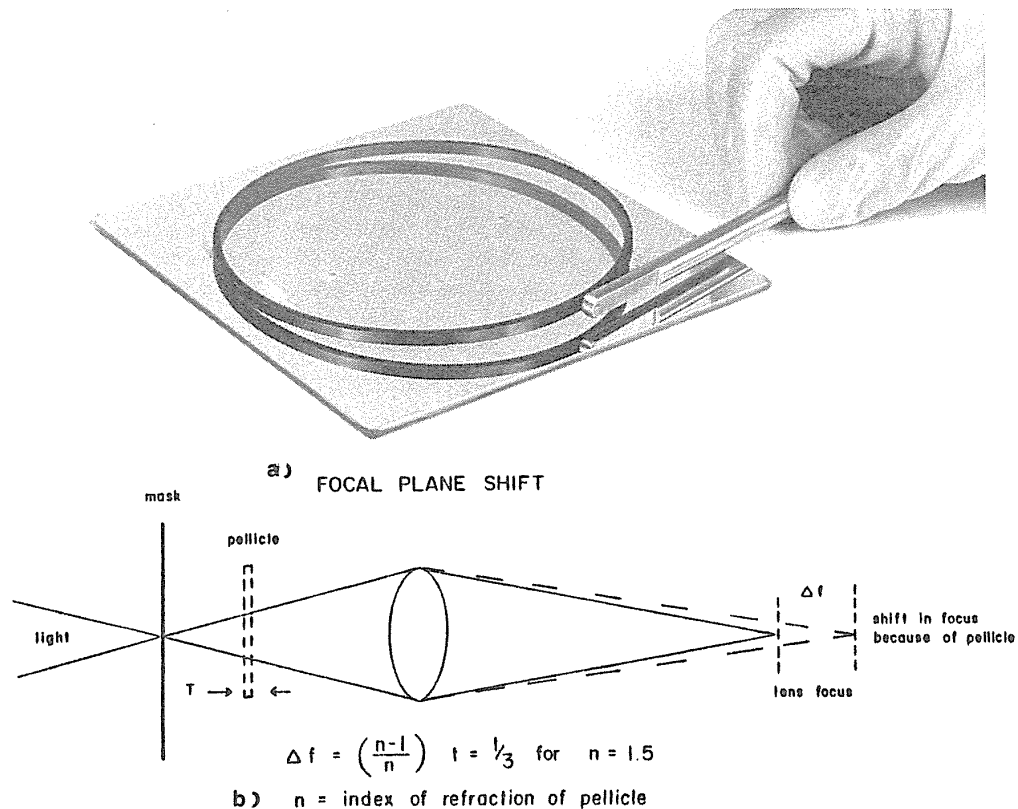


Fig. 29 (a) Photograph of a pellicle. Courtesy of EKC Technology. (b) Focal plane shift of a pellicle.

particulates. Fingerprints can be cleaned by using a mild surfactant and manual scrub. The glass (back) side of the mask is usually cleaned at the same time. Damaged pellicles can be successfully replaced if careful mask cleaning and inspection is done prior to attaching the new unit. With the exception of a few IC manufacturers, use of pellicles has become an industry standard.

Inspecting Masks and Reticles with Pellicles Attached

The process of attaching a pellicle to a defect-free mask or reticle should itself not create defects on the mask. For example, a zero defect reticle may become useless due to contamination under the pellicle. To insure that the assembly procedure has not introduced any defects, a post-pellicle inspection procedure should be performed. Van Asselt and Brooks⁴⁷ suggest a method for performing such an inspection. The mask-pellicle assembly is mounted in a projection aligner and is used to expose round, thin glass plates (glass wafers), coated with chromium and resist. The wafers are exposed, developed, etched, and stripped to produce an image suitable for inspection by transmitted light. The processed glass wafers are then inspected on an automatic mask inspection system with a special mask holder. Defects located by the inspection system that coincide in location on two or more glass wafers are attributed to defects that occurred as a result of the pellicle attachment procedure, while defects occurring in only one location can be associated with the processing of that particular wafer. The procedure can be extended to multiple-die reticles used in 1X and 5X stepping systems.

Critical Dimension and Registration Inspection of Masks and Reticles

Upon completing the fabrication of a reticle or mask, it must be inspected to verify that the fabrication was correctly carried out⁴⁸. The detection of fabrication process-induced defects was described earlier. In this section inspection procedures of the following mask and reticle characteristics are discussed: a) physical characteristics (e.g. title correctness, polarity of the field of the primary and test patterns, substrate [glass] type, chrome type [i.e. shiny, low reflective, or medium reflective]; b) critical dimensions (CD); and c) registration. The ability to effectively perform the full gamut of inspections on VLSI masks or reticles involves the use of a set of complex and expensive inspection tools.

Checking the *physical characteristics* requires the least complex inspection equipment (e.g. an optical microscope and video measurement device), but detected flaws can still force the rejection of a finished plate. Since the inspection can be relatively easily performed, some users request a *check plate* prior to initiating the full tooling fabrication sequence. A check plate can be made on a low-cost blank, allowing for early detection and correction of physical flaws.

The subject of linewidth measurement was covered in Chap. 12, and the same types of linewidth measurement techniques used to measure CDs in developed resist patterns can be used to measure mask feature dimensions. As pointed out in Chap. 12, the task is considerably easier on a mask or reticle, because the chrome pattern layer is relatively thin (making accurate edge detection easier), and the topography under the chrome is flat, unlike the topography on a wafer near the end of the fabrication cycle. Linewidth standards are available from the NBS for mask and reticle feature dimension measurements.

The ability to perform both inspection of *critical dimensions* and *registration* on VLSI masks or reticles with a single machine, however, requires a sophisticated metrology instrument, such as the Nikon 2I[®] system. This is an interferometry tool containing two instruments: 1) a Nikon Lampas[®] head which uses a laser beam to detect pattern edges; and 2) an x-y stage for precisely determining position. Together, they allow the tool to measure both CDs and registration accuracy. While a 10X reticle commonly contains only a single pattern, 5X reticles and 1X masks typically have an array of patterns. In addition to the repeated primary die patterns, the finished plate may contain test strips, array alignment marks, and global alignment marks. It must be determined that each of these patterns is located at the specified coordinates.

If a specific metrology instrument is utilized for both the registration and CD inspection, the alignment marks and CD test patterns may need to be placed on specific locations of the plate. For example, a popular method used with the Nikon 2I is to combine the CD and registration marks into one feature and to place these at the corner of each die of the array. The dimensions of CD marks are compared to a known standard, and registration marks to other levels within the device. Presently, inspection for process-induced defects and CD /registration inspection is done on different systems. It is postulated that future metrology requirements will dictate that a single machine which combines both capabilities be available (i.e. one that is able to detect, measure, and classify defects, and also to perform a die-to-database inspection and CD /x-y coordinate measurements). The Wafervision[®] system introduced by Contrex is designed as such a "universal" inspection system⁴⁹.

REFERENCES

1. L.F. Thompson and M.J. Bowden, "The Lithographic Process: The Physics" in *Introduction to Microlithography*, American Chem. Society, Advances in Chem. Ser., Vol. 219, 1983, p. 15.

2. B.T. Lin, "Optical Methods for Fine Line Lithography" in R. Newman, (ed.), *Fine Line Lithography*, North Holland, Amsterdam, 1980.
3. E.B. Brown, *Modern Optics* (Van Nostrand-Reinhold, New York, 1965).
4. J.E. Roussel, "Submicron Optical Lithography?", *SPIE Proc. Vol. 275, Semiconductor Microlithography*, 1981, p. 9.
5. M.C. King, "Principles of Optical Lithography", in N.G. Einspruch (Ed.), *VLSI Electronics Micro Structure Science*, Vol. 1, Academic, New York, 1981.
6. K.L. Tai, *et al.*, *J. Vac. Sci. Technol.*, **17**, 1169, 1980.
7. J.G. Skinner, "Some Relative Merits of Contact, Near-Contact, and Projection Printing", *Proc. Kodak Interface*, **73**, 53 (1973).
8. D.J. Elliot, *Integrated Circuit Fabrication Technology*, McGraw-Hill, New York, 1982, Chap. 8, Exposure, p. 165.
9. P. Burggraaf, "Wafer Steppers and Lens Options", *Semiconductor International*, Mar '86, p. 56.
10. P. Burggraaf, "Advances Keep Optical Aligners Ahead of Industry Needs", *Semiconductor International*, Feb. 84, p. 88.
11. V. Miller and H. Stover, "Sub-Micron Optical Lithography, I-Line Wafer Stepper and Photoresist Technology", *Solid State Technol.*, Jan. 85, p. 127.
12. M.M. O'Toole and A.R. Neureuther, "Influence of Partial Coherence on Projection Printing", *SPIE Proc. Vol. 174, Developments in Semiconductor Microlithography*, 1979, p. 22.
13. J. Roussel, "Step and Repeat Wafer Imaging", *SPIE Proc. Vol. 135, Developments in Semiconductor Microlithography III*, 1978, p. 30.
14. N. Gold, "Spectral Exposure Meter", *SPIE Proc. Vol. 334, Optical Microlithography Technology for the Mid-'80s*, (1982), p. 70.
15. R.C. Bracken and S.A. Rizvi, "Microlithography in Semiconductor Device Processing", in N.G. Einspruch and G.B. Larabee, (Eds.), *VLSI Electronics-Microstructure Science*, Vol. 6, Academic, Orlando, Fla., 1983, Chap. 5, p. 256.
16. D.A. Markle, *Solid State Technology*, p. 50 (June '79).
17. M.C. King, "New Generation of 1:1 Optical Projection Aligners", *Proc. SPIE Vol. 174, Developments in Semiconductor Microlithography IV*, 1979, p. 70.
18. A.N. Broers, "The Submicron Lithography Labyrinth", *Solid State Technol.*, June '85, p. 119.
19. W. Carpenter, "Mixing 1X Scanning and 5X Step-and-Repeat Exposure Systems in a Semiconductor Processing Line", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 38.
20. H.L. Stover, "Near Term Case of 5X versus 10X Steppers", *SPIE Proc. Vol. 334, Optical Microlithography-Technology for the Mid-80's*, 1982, p. 60.
21. R. Hershel, "Characterization for the Ultratech Wafer Stepper", *SPIE Proc. Vol. 334, Optical Microlithography-Technology for the Mid-80's*, 1982, p. 44.
22. M.S. Chang, "One Micron 1X Stepper Photolithography: An Introductory View", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 32.
23. P. Burggraaf, "Reduction Reticle Trends:Emphasizing 5X", *Semiconductor Intl.*, Aug.'84, p. 59.
24. B. Heflinger, "Comparison of Autoalign Techniques", *Proc. SPIE, Vol. 334, Optical Microlithography*, 1982, p. 70.
25. P. Swanson, G. Alonzo, J.Dey, "Automatic Self-Testing of Machine-to-Machine Matching of Wafer Steppers", *SPIE Proc. Vol. 470, Optical Microlithography III*, 1984, p.185.
26. A variety of articles dealing with automatic alignment are published in the *Proc. SPIE, Optical Microlithography III and IV*, 1984, and 1985.
27. D.A. McGillis, "Lithography", in *VLSI Technology* [S.M. Sze, Ed.], McGraw-Hill Book Co., New York, 1983, Chap. 7, pp. 267-301.
28. *ibid.*, Ref. 8, Chap. 14, "Mask Fabrication", p. 339.

29. R. Iscoff, "Photomask and Reticle Materials Review", *Semiconductor Internatl*, Mar '86, p. 82.
30. T. Yamazaki, *et al.*, *Japanese Jnl of Appl. Phys.*, **19**, 1371, (1980).
31. B. Hasler, German Pat. 2,738,839 (Siemens AG).
32. B.J. Curtis, H.R. Brunner, and M. Ebnoether, "Plasma Processing of Thin Chromium Films for Photomasks", *J. Electrochemical Soc.*, **130**, 2242 (Nov. 1983).
33. *ibid.*, Ref. 15, p. 260-292.
34. P. Singer, "Merchant Mask-Making in State of Change", *Semiconductor Intl.*, Mar '86, p. 45.
35. *ibid.*, Ref. 15, p. 266-272.
36. S.N. Gupta, *et al.*, "Multiple Flash Overlap Defect in Photomasks", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 153.
37. CORE 2000, *Semiconductor International.*, Oct. '85, p. 29-30.
38. A.C. Titus, "Photomask Defects: Causes and Solutions", *Semiconductor Intl.* Oct. '84, p. 94.
39. K.L. Harris, *et al.*, "Automated Wafer Inspector Characterization", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 138.
40. L.H. Lin, *et al.*, "A Holographic Photomask Defect Inspection System", *SPIE Proc. Vol. 538, Optical Microlithography*, 1985, p. 110.
41. R.V. Fraser and B.A. Wallman, "Database Inspection of Wafer Resist Images", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 122.
42. R.T. Hilton, *et al.*, "Glass Wafer Processing and Inspection for Qualification of Reticles in a Fineline Wafer Stepper Production Facility", *SPIE Proc. Vol. 538, Optical Microlithography*, 1985, p. 117.
43. G. Hearn, "Repair of Both Clear and Opaque Mask Defects", *Microelectronics Manufacturing and Testing*, Oct. 1985, p. 19.
44. R. Herschel, "Pellicle Protection of Integrated Circuit Masks", *SPIE Proc. Vol. 275, Semiconductor Microlithography VI*, 1981, p. 23.
45. J. Lent and S. Swayne, "Implementation of Pellicles Into An Established Production Area", *Proc. Kodak Interface*, 1982, p. 93.
46. A. Flamholz, "An Analysis of Pellicle Parameters for Step-and-Repeat Projection", *Proc. SPIE, Vol. 470, Optical Microlithography III*, 1984, p. 138.
47. R. VanAsselt and G. Brooks, "Technique for Inspecting Photomasks with Pellicles Attached", *Proc. Kodak Interface*, 1982, p. 158.
48. P. Chipman, "Qualifying Reduction Reticles", *Semiconductor International*, Aug. '84, p. 68.
49. M.L. Baird, *et al.*, "Extending the Limits of Pattern Inspection Using Machine Vision", *SPIE Proc. Vol. 538, Optical Microlithography IV*, 1985, p. 130.
50. G. Zinsmeister, "Hard Surface Mask Technology", Technical Handout from IGC Conference on Microlithography, Amsterdam, Holland, September, 1979.

PROBLEMS

1. Explain why information about the edge of features on a mask is only contained by diffracted light and not by the undiffracted light that reaches the wafer surface.
2. Explain why an extended source appears as an incoherent source of radiation, and how the use of an entrance pupil (Fig. 5b) is used to control the degree of partial coherence in a source.
3. Calculate the minimum distance that can be just resolved (Rayleigh limit) by a 0.16 NA lens when (a) G-line radiation and (b) I-line radiation from a mercury-arc spectrum is used. Repeat this exercise for an 0.28 NA and an 0.35 NA lens.
4. As the NA of a lens is increased, the image field diameter decreases. For a 150 mm diameter wafer, how many exposures would be necessary to completely expose a resist layer, if a

- step-and-repeat refractive projection aligner with a lens of (a) 0.28 NA, and (b) 0.35 NA was used.
5. Determine the minimum sized line that can be printed by a projection aligner that has a lens with an NA = 0.28, uses a G-line radiation source, and has a coherence of (a) $s = 0$, (b) $s = 0.7$, and (c) $s = \infty$. Assume the resist being used has a $\gamma = 2$. Express your answer in μm . Repeat the problem for the case when the NA of the lens is increased to 0.35. Repeat the initial problem again if a resist is used which has a $\gamma = 7$.
 6. Discuss the problems of (a) *ringing*, as the spatial coherence of the source is increased, and (b) *decrease of the depth of focus* as the NA of the lens is increased. How do these limitations effect the quality of the transferred image on a wafer?
 7. Discuss the differences in the principles of operation of (a) scanning projection aligners, (b) reduction refractive step-and-repeat aligners, and (c) 1X step-and-repeat aligners.
 8. Assume that the values of σ_{p1} , and σ_{p2} in a process line are $\pm 0.1 \mu\text{m}$ and the value of $\sigma_r = \pm 0.15 \mu\text{m}$. Find the registration tolerance that must be incorporated by the circuit designers into the mask dimensions to insure that there will be a probability of $< 0.1\%$ that the edges of features patterned by two different mask layers will touch.
 9. Show how the intensity pattern obtained from the automatic alignment marks shown in Fig. 19 can yield information about how well the mask is aligned to the patterns already present on a wafer surface.
 10. Explain the difference between the *die-to-die* and *die-to-database* inspection methods of masks (and reticles). Where does each of these inspection techniques find application?
 11. Explain why *clear defects* in a mask or reticle are more difficult to repair than *opaque defects*. Why has the traditional *lift-off* technique for opaque mask repairs been found less than suitable for the repair of VLSI masks and reticles?
 12. Describe the two types of inspection systems that must be used to completely inspect a mask or reticle after it has been fabricated. Explain the use of *glass wafers* in reticle qualification.

ADVANCED LITHOGRAPHY

The resolution and registration (3σ) of optical lithography is limited to somewhat less than $1\text{ }\mu\text{m}$, and $\pm 0.3\text{ }\mu\text{m}$, respectively. To extend the capability of the lithographic pattern transfer process beyond these limits, alternatives to optical lithography have been developed, including: a) electron beam lithography, which offers resolution of $0.375\text{ }\mu\text{m}$, with $\pm 0.05\text{ }\mu\text{m}$ (3σ) registration; b) x-ray lithography, $0.25\text{ }\mu\text{m}$ resolution with $\pm 0.3\text{ }\mu\text{m}$ (3σ) registration; and c) ion beam lithography ($\sim 0.2\text{ }\mu\text{m}$ resolution). These advanced lithographic processes are the subject of this chapter. In Chap. 13, the use of electron beam lithography to produce photomasks was described. The present discussion will therefore emphasize the direct wafer exposure applications of electron beam lithography, although the equipment used to perform both tasks will be covered.

ELECTRON BEAM LITHOGRAPHY

Electron beam (or e-beam) lithography (EBL) is the process of forming circuit patterns by using a focused electron beam. Such beams can be readily scanned and accurately positioned on the substrate to expose radiation-sensitive material (e-beam resist). The early e-beam machines were modifications of commercial scanning electron microscopes.

Early workers quickly realized the potential advantages of EBL over optical lithography, including: a) EBL provides the ability to produce features less than $1\text{ }\mu\text{m}$ directly on a wafer, without the use of a mask, and under the control of a computer; and b) an e-beam can be used to accurately detect features on a substrate. This ability can be used to provide extremely accurate layer-to-layer registration. Features as small as $0.1\text{ }\mu\text{m}$ have been made with this technique. This is possible because, although electrons do possess wave-like properties, for the energies used in EBL systems, their wavelengths are on the order of $0.2\text{--}0.5\text{ \AA}$. As a result, diffraction effects which limit resolution in optical lithography are avoided.

There are, however, limitations which have kept EBL from being widely incorporated into VLSI fabrication environment, including: a) resolution is limited by the fact that the electrons are forward scattered in the resist and backscattered from the substrate. This results in exposure of the resist outside the desired areas; b) resolution is also limited by a resist processing phenomenon termed *swelling*, which occurs upon development of negative e-beam resists; c) EBL is extremely slow when compared to optical projection and step and repeat systems; and d) EBL systems are 3 to 5 times more expensive than optical steppers, and generally require more expensive facilities.

Table 1. E-BEAM SYSTEM ACCURACY SPECIFICATIONS, for an AEBLE™150¹

Minimum Feature Size	0.5 μm	Overlay Accuracy	$\leq 0.15 \mu\text{m}, 3\sigma$
Line Edge Roughness	$\leq 0.08 \mu\text{m}, 3\sigma$	Dimensional Accuracy	$\leq 0.08 \mu\text{m}, 3\sigma$
Field Butting Error	$\leq 0.15 \mu\text{m}, 3\sigma$	Address Structure	0.0156 μm (1 / 64 μm)

The potential advantages of EBL, however, have prompted the commitment of significant development efforts towards overcoming its limitations. These efforts are beginning to pay off as machines with improved throughput times (e.g. 4-6 100 mm wafers per hour) are coming to market (e.g. the AEBLE™-150 from Perkin-Elmer)¹. Table 1 lists the specifications for a state-of-the art EBL system used for direct-write on wafers.

Electron Beam Systems

EBL systems that have gained in popularity use scanned, focused e-beams which expose the resist in a serial manner. Figure 1 shows the main features in a simplified form of an EBL system². There are five main sub-systems: 1) the electron source (or gun); 2) the electron column; 3) the mechanical stage; 4) the wafer handling system; and 5) the control computer.

To write submicron features, the e-beam must be generated, and then focused into a small diameter spot. To obtain short resist exposure times, the current density in the focused spot must also be high. The electron beam is produced by an *electron source*. There are two types of electron sources commonly used in EBL systems: a) thermionic sources; and b) field-emission sources. Note that electron sources are also discussed in Chap. 17, in the discussion on scanning electron microscopes. *Thermionic sources* utilize a material which is heated to the elevated temperatures at which electrons are emitted. Candidate materials for this application are tungsten (W), thoriated tungsten, and lanthanum hexaboride (LaB_6). The *W sources* have been the most widely used as they provide a stable current and exhibit excellent tolerance to vacuum conditions. The maximum brightness of such sources is $1\text{-}3 \times 10^5 \text{ (A/cm}^2\text{) /steradian}$. The

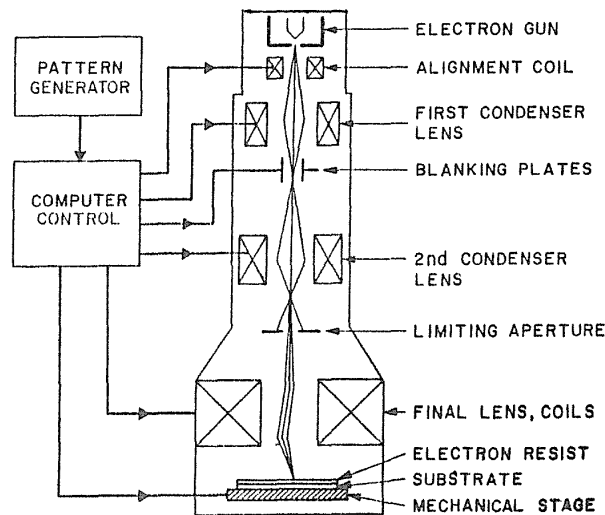


Fig. 1 Schematic of an electron beam machine. From Kern, *et al*, *Solid State Technol.*, 27, 1984, p. 127. Reprinted with permission of Solid State Technology, published by Technical Publishing, a Company of Dun & Bradstreet.

thoriated tungsten sources have a lower work function, thereby providing currents comparable to standard W sources, but at lower temperatures. This leads to longer life and better beam stability. The fabrication of thoriated W sources, however, is difficult and their use requires very stable vacuum conditions. The LaB_6 source has even a lower work function than the previous two sources and can provide a brightness of 10^6 (A/cm²)/steradian. LaB_6 sources, however, exhibit less stability and require better vacuum conditions than the other two sources. Nevertheless, they can emit over an extended area, which allows them to be used in shaped beam systems, and because of their advantages they are becoming the standard emitter for EBL systems. For example, the MEBES III system, which is a Gaussian beam type EBL system, uses a LaB_6 source, as do the variable shaped beam systems.

In *field emission sources*, a very high electric field at the sharp tip of an emitter extracts electrons, which form a fine Gaussian spot. These sources are brighter than the thermal emitters, having a brightness of 10^8 to 10^9 (A/cm²)/steradian. They are difficult to fabricate, however, and require high vacuum (10^{-8} - 10^{-10} torr) for effective operation. The Electron Beam Corporation direct-write system uses a thermal field emission source to achieve high brightness³.

The *electron column* consists of (at a minimum): a) the electron source; b) various lenses used to focus and magnify or demagnify the beam; c) a beam blanker to turn the beam on and off; d) various apertures to limit and shape the beam; and e) a beam deflection system to position the beam on the substrate. Figure 2 shows a schematic of the electron column used in the Perkin-Elmer AEBLE-150 direct-write system. E-beam machines used in research applications must provide the smallest possible spot to achieve the high resolution (e.g. some machines are capable of producing beam spot sizes of $\sim 500\text{\AA}$). On the other hand, e-beam systems dedicated to the production of photomasks with feature sizes of 1.0-4 μm can operate effectively with a relatively large beam diameter (e.g. 0.25-1.0 μm). Since most thermionic electron sources produce electrons from a cathode that is 10-100 μm in diameter, in order to achieve submicron spots, electron-optical demagnifying lenses are required to reduce the beam diameter from 100-1000 times. The lenses of the system are also designed to minimize aberration, which is one of the parameters that limits the resolution of the system. The price paid for reducing aberration is that the area over which the beam can be scanned is limited.

In order to write over an entire wafer (e.g. 150 mm diameter), a *mechanical stage* is used to position the substrate under the e-beam. The position of the stage must be accurately known at all times, and this position is usually controlled by a laser interferometer to better than 1/64 μm . The velocity of the stage is important in determining the throughput of the system, because patterns can be written after the stage position has been determined. It is also possible to perform a registration at this time. On the other hand, it is possible to write the pattern "on the fly". The stage position must be accurately known at any instant so corrections can be made by the deflection system. The AEBLE-150 has a stage that achieves a velocity of 10 cm/sec, a 50 ms stepping time for 2 mm step, a positional accuracy of 0.5 μm , and no vibration >200 Hz.

An important part of an effective EBL system is its ability to automatically handle wafers, and then feed them into the beam as required. In this way a batch of wafers can be run unattended. Such a handling system must be able to pre-align wafers, and to introduce them into the high-vacuum environment of the stage without degrading the vacuum. The AEBLE-150 wafer handling system is capable of loading a 25-wafer cassette of 150 mm wafers. The wafer is taken from the cassette and transported to the wafer aligner, where it is aligned with respect to its primary flat, and then oriented along its x, y, and z axes. The wafer is next placed on a chuck, which is then loaded on a pallet on rollers that can be pushed through the airlock and loading chambers to the work chamber. Substrate exchange occurs in less than 30 sec. The wafer is held by electrostatic forces within the work chamber. When the exposure is complete, the pallet is

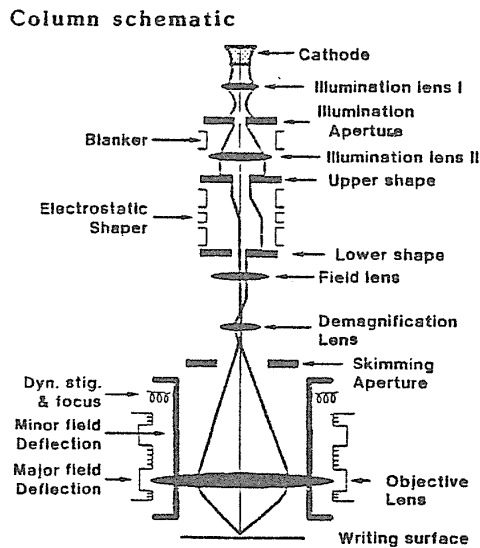


Fig. 2 Electron column used in the Perkin-Elmer AEBLE-150 system. Courtesy of Perkin-Elmer.

removed back through load and airlock chambers to the output cassette. A new wafer is then loaded on the pallet and chuck.

All of these sophisticated sub-systems must operate correctly, and in unison. This requires control by a computer system. The system operates in real time for control functions of the stage position and column. In addition, the computer controls the electron beam size, exposure time, stage position, and data processing for alignment and calibration. It can also monitor the column, beam quality (focus, current density, and alignment), and spot shape and size. The pattern data must also be rapidly transferred to the deflection and blanking systems. The data transfer rate is generally high enough not to limit the throughput of the machine. Higher performance systems are now available as a result of fast, high density computer memory that has become available at low prices.

Writing Strategies

The writing strategy of an EBL system includes: a) the shape of the beam; and b) the method of scanning the beam over the wafer. The substrate to be exposed is subdivided into a grid of addressable locations. Each of these locations represents a *pixel*. A pixel defines the minimum resolution element that can be generated by the specified electron dose. The pixels are joined to create pattern shapes, and the minimum observable pattern is one pixel exposed and one not exposed. If the pixel size is $0.5 \mu\text{m} \times 0.5 \mu\text{m}$, a 150 mm wafer would contain $\sim 7.5 \times 10^{10}$ pixels. To form an acceptable image in the resist, a minimum number of electrons, N_m , must impinge upon each exposed pixel (Fig. 3). For a given resist sensitivity, S (defined in units of C/cm^2), this minimum is given by:

$$N_m = \frac{S l_p^2}{q} \quad (1)$$

where l_p is the minimum pixel dimension, and q is the electron charge.

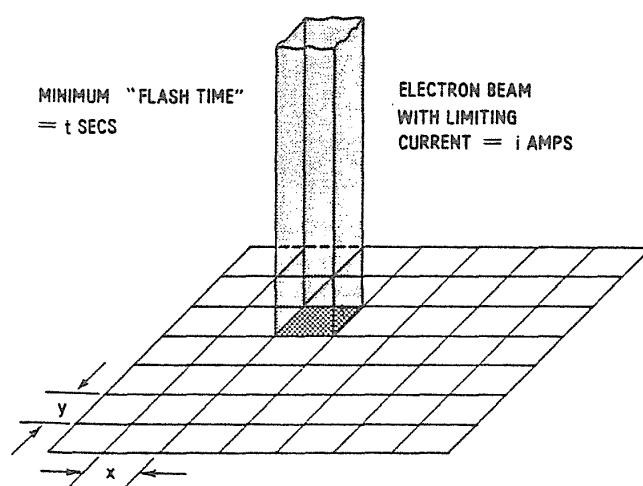


Fig. 3 Schematic of exposure of a unit address of resist surface. Reprinted with permission from Ref. 7, 1983, American Chemical Society.

Beam Shape

Two alternative types of electron beams are used for EBL: a) the Gaussian shaped round beam^{2,4} (Fig. 4a); and b) the variable shaped beam^{2,5} (Fig. 4b). The *Gaussian round beam* is typically four times smaller than the smallest pattern dimension. The *variable shaped beam* (VSB) is varied to match the feature size (i.e. larger pattern areas can be exposed by increasing

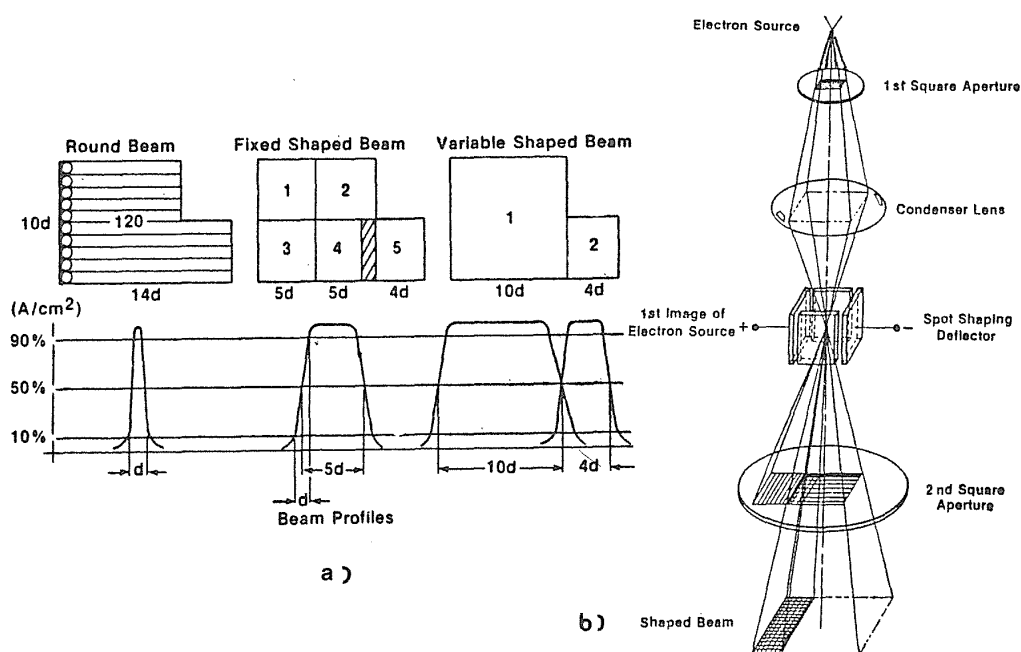


Fig. 4 (a) Pattern generation and beam profiles²⁸. (b) Variable shaped beam forming principle²⁹. Reprinted with permission of Solid State Technology, published by Technical Publishing, a Company of Dun & Bradstreet.

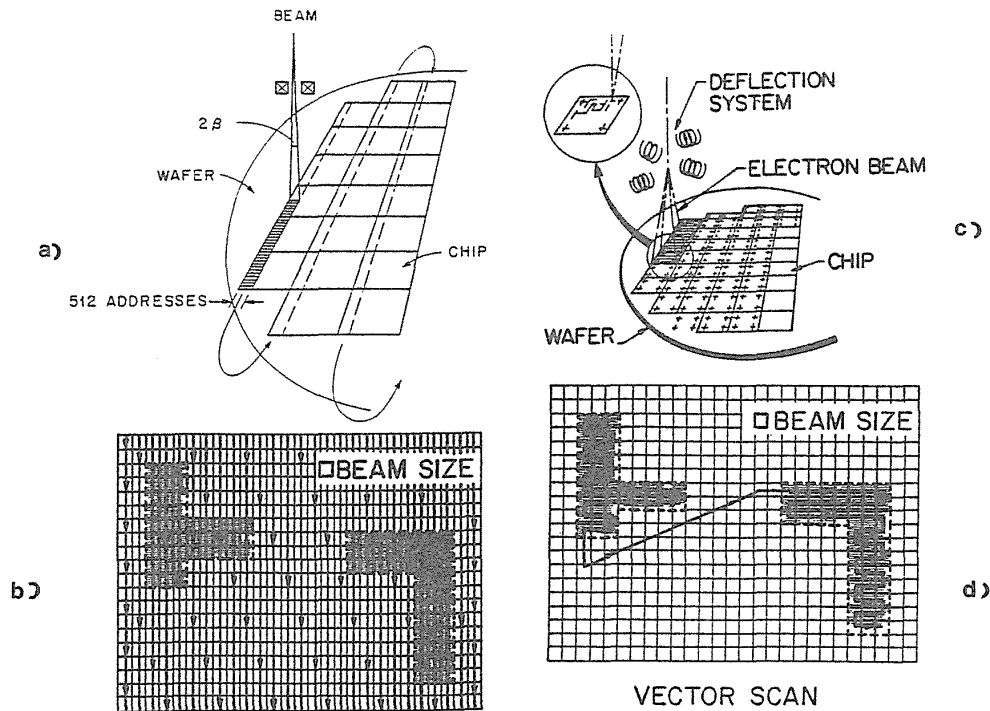


Fig. 5 (a) and (b) Raster scan exposure scheme. (c) and (d) Vector scan exposure scheme. Reprinted with permission of Ref. 7., 1983, American Chemical Society.

the size of the beam). On the average, the shaped beam simultaneously exposes about 30 pixels.

Throughput is higher with the VSB, but not by as much as is indicated by the ratio of the beam areas. This results from electron-electron interactions which impose a maximum limit on the current of a shaped beam. For beam currents greater than a few microamperes, the edge definition becomes limited by aberrations from such electron-electron interactions, rather than by a combination of beam brightness and deflection aberrations. The full brightness of the electron gun, therefore, cannot be used for shaped beams, but can be for the round beams.

The VSB, which is becoming the choice for high throughput EBL systems, is formed by illuminating a square aperture with a uniform flood of electrons. Its image is then projected onto a second square aperture. This produces a rectangular spot. The dimensions of the spot can be set by deflecting the image of the first aperture to impinge on the second aperture in the appropriate position (Fig. 4b). The AEBLE-150 system utilizes a VSB which can produce rectangles or 45° triangles of any size from 0.3-2.0 μm .

Scanning Systems

After the beam is focused and shaped it requires scanning (deflection) over the substrate. Deflection is generally accomplished electromagnetically, although electrostatic systems also exist. The AEBLE-150 utilizes magnetic deflection over a 2 mm x 2 mm field, while an electrostatic deflector provides high speed scanning over a 64 μm minor field.

The *raster technique* scans the beam over the entire substrate and is turned on and off according to the desired pattern^{2,6,13}. The chip is broken down into stripes of typically 256

address units (AU), and deflected over that range. A laser controlled table moves the substrate along the AU stripe in the x-direction, while the beam is sweeping out one scan line in the y-direction. Figure 5a shows a schematic representation of this technique.

The *vector scan system* aligns the individual die or chip, then exposes it with a two-dimensional electronic scan that covers the entire area^{2,6,13}. Since the scan area is smaller than a chip area, it is required to mechanically move the sample. This can be accomplished by step and repeat movement, or by continuous mechanical scanning. Figure 5b shows a schematic of the vector scan. The AEBLE-150 uses the vector scan mode where a major field is 2 mm x 2 mm, and nested. Within that field is a minor scan field of 64 μm x 64 μm .

Since a single chip is typically larger than the area scanned by the major field, continuity across field boundaries must be considered. The degree of misalignment across a field boundary is called the *butting error*. The AEBLE-150 boasts a butting error of $<0.15 \mu\text{m}$ (3σ) for both the major and minor fields.

The registration of a layer can be accomplished in three ways: a) on a global basis; b) on a die-by-die basis; or c) on a field-by-field basis. In the *global system* the wafer is first accurately aligned, and then accurately positioned by the laser controlled table. This assumes extreme stability of the system, and flat, non-distorted wafers. In the *field-by-field* (and *die-by-die*) methods, special alignment marks are present which allow alignment at each major field (or die). These marks need to be compatible with the process, so they can be recognized by the detector system throughout the entire processing sequence.

Alignment marks may consist of either a high Z (atomic number) metal pedestal, or (more likely) a feature etched in the silicon or SiO_2 . The alignment is achieved by detecting backscattered electrons from such marks. Along the edge of the mark, the electron signal is reduced because of scattering at various angles.

Electron Scattering and Proximity Effects in Resists

During e-beam exposure the electrons entering the resist are scattered (forward and back) by interaction with the atoms of the resist and the substrate. Most of the electrons are forward scattered through small angles ($< 90^\circ$) from their original direction. This, in effect, broadens the beam. Some of the electrons experience large angle backscattering (e.g. $>180^\circ$), causing them to return toward the surface. Figure 6 shows the results of a Monte Carlo calculation of trajectories for 100 electrons projected onto the x-z plane for 10 and 20 keV point sources⁷. The degree of forward and backscattering predicted by the calculation is illustrated in the pictorial representation.

Figure 7 shows the effect of this scattering on a beam that strikes a resist-coated surface⁸.

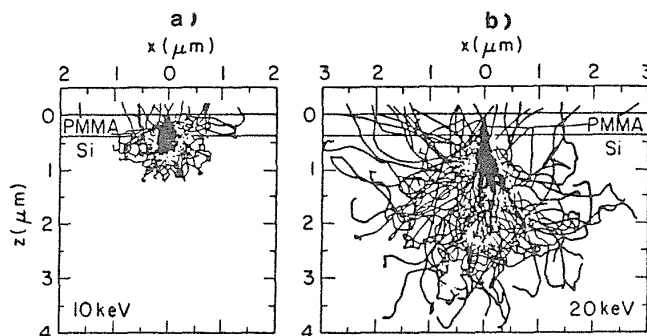


Fig. 6 Simulated trajectories of 100 electrons in PMMA. (a) Simulation for a 10 keV beam. (b) Simulation for a 20-keV beam³¹. Reprinted with permission of the Electrochemical Society.

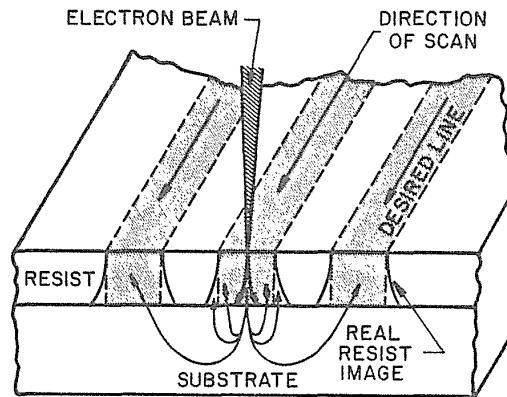


Fig. 7 Electron scattering effects in resist-coated substrate⁸. Reprinted with permission of Semiconductor International.

First, it is seen that the scattering broadens the incident electron beam. Second, the electrons backscattered from the substrate return through the resist, contributing to additional resist exposure. This results in a developed image wider than anticipated from the beam diameter alone. Such scattering is thus one of the mechanisms that limits the minimum linewidth. Since the scattering can extend over several microns, closely spaced patterns will receive electrons from the exposure of their neighbors. This is termed the *proximity effect*.

The absorbed energy density in the resist is given by⁸:

$$E(r) = k \left[\exp\left(-r^2/\beta_f^2\right) + n \frac{\beta_f^2}{\beta_b^2} \exp\left(-r^2/\beta_b^2\right) \right] \quad (2)$$

where k is a proportionality constant, n is the ratio of total energy deposited by the backscattered electrons to that deposited by the forward scattered electrons, β_f and β_b are the characteristic widths of the forward scattered and backward scattered Gaussian distributions, and r is the radial distance from the center of the spot. The parameters β_f , β_b , and n vary with energy, while β_b and n also vary with substrate material. The adjustment of these three parameters with exposure and substrate conditions is used for proximity effect corrections in device writing.

Figure 8 illustrates some other consequences of the proximity effect on a developed image. At point A (the center of a large exposed area), we see that there are energy contributions from

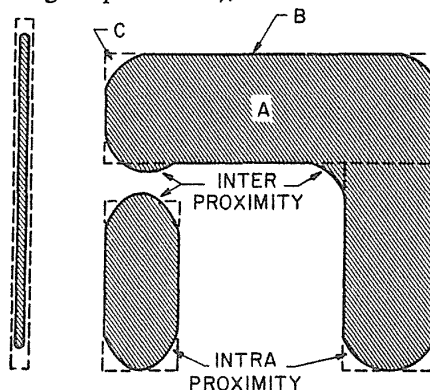


Fig. 8 Inter and intra proximity effects in e-beam exposure caused by electron scattering⁸. Reprinted with permission of Semiconductor International.

surrounding electrons. At the corners and edge of this large exposed pattern, however, the same total dose is not received. For example, at the edge (point B), only half the dose of point A is received, and at the corner (point C), only one fourth the dose of point A. As a result, upon development, which is optimized for the main pattern, the corners are not developed to their full design size. This phenomenon is referred to as an *intra-proximity effect*, and causes large and small feature sizes to print differently.

For the case of a long narrow line (left of Fig. 8), if the exposure and develop cycle is chosen to obtain the proper edge at B, the narrow lines will be too narrow. On the other hand, since backscattered electrons travel over large distances, adjacent patterns may exhibit cooperative exposure effects if they are closely spaced. This is known as an *inter-proximity effect*, and results in the bulging of patterns towards one another (Fig. 8). Under extreme conditions, bridging of the features can occur.

An understanding of these effects allows the dose to be properly compensated if the circuit pattern and the degree of scattering are identified. That is, the circuit can be broken into primitive shapes (rectangles) and the local dose altered for each shape. Thus, the developed image is produced with the proper dimensions. Programs are available which use Eq. 2 to control the dwell time of the beam in the local area, to adjust for these effects. A throughput penalty may be incurred as a result, since increased computer time will be necessary to partition and expose the subdivided resist features.

The use of multi-layer resist techniques has overcome many of the problems of proximity effects and linewidth control. The thick planarizing layer absorbs backscattering electrons, minimizing their effect on neighboring resist. Multi-level resist systems do, however, add processing complexity and create problems with registration mark recognition⁹.

Electron Resists and Resist Development

Electron beam resists are materials in which chemical or physical changes are induced upon exposure to the high energy electron beam, which allows the resist to be patterned. Exposure to such electrons typically causes two types of changes in e-beam resist material: a) radiation-induced polymer cross-linking (in negative resists); and b) chemical bond breaking (in positive resists). Table 2 lists the various resists and compares their sensitivity, resolution, and etch resistance¹⁰. The sensitivity, S , for negative resists is defined as the electron dose /cm² required to retain 50% of the resist in the exposed areas, while for positive resists, it is the dose required to generate a solubility ratio of 50.

Negative electron resists are polymer chains which chemically cross-link upon absorption of energy from the e-beam to form a complex molecular network. The average molecular weight (MW) increases as a result of the cross-linking, until the material is no longer soluble in the solvents used for the starting polymer. Unfortunately, the solvents used to remove the unexposed resist result in swelling of the exposed area during development (as in the negative optical resists described in Chap. 12), and limits negative e-beam resist resolution to ~1.0 μm .

The most widely used commercial negative resists are poly(glycidyl methacrylate) monopolymers (OE8R 100, manufactured by Tokyo Okha), and copolymers (COP, manufactured by Mead), which both exhibit sensitivities of 0.7 $\mu\text{C}/\text{cm}^2$, and resolutions of 1.5 μm . Recent activity has focused on sensitive poly (styrene) derivatives which have high contrast, require no post-curing, and exhibit high dry etch resistance (e.g. poly (chlorostyrene) and poly (iodostyrene) [RE 400 DN, manufactured by Hitachi]). The formulation of a sensitive (0.5 $\mu\text{C}/\text{cm}^2$) resist with 1 μm resolution capabilities has been reported by Hewlett-Packard [poly-(chloromethylstyrene)]¹⁰.

Table 2. THE PERFORMANCE OF ELECTRON BEAM RESISTS¹⁰

	Image Type	Trade Name	Manufacturer	Sensitivity ($\mu\text{Coul}/\text{cm}^2$)	Resolution (μm)
Poly(glycidyl methacrylate)	-	OEBR100	TO	0.7	1.5
PGMA co poly(ethyl acrylate)	-	COP	MD	0.7	1.5
Poly(chloromethylstyrene)	-		HP	0.5	1.0
Poly(iodostyrene)	-	RE4000N	H	1.8	1.0
Poly(methylmethacrylate)	+	PMMA	N	80	0.05
PMMA co poly(acrylonitrile)	+	OEBR1030	TO	30	< 0.5
Poly(trifluoro- α -chloroacrylate)	+	EBR 9	T	15	< 0.5
Poly(fluroalkylmethacrylate)	+	FBM	DK	??	< 0.5
PMMA Xlinked	+	PM	M	40	< 0.5
Poly(butene sulphone)	+	PBS	MD	2.0	0.5
Novolac - diazoquinone resist	+	AZ 1350	AZ	15/50	0.5
Novolac-poly(methylpentene sulphone)	+	RE 5000P	H	5.0	< 0.5
Poly(styrene)-tetrathiofulvalene	$\pm$		IBM	8.0	< 0.5
Inorganic GeSe /AgSe	-		N	500	< 0.5
Poly(siloxane)	-		IBM	1.5	< 0.5

Company codes: TO = Tokyo Okha, MD = Mead, HP = Hewlett-Packard, TS = Toyo Soda,
N =Numerous, DK = Daikin Kogyo, M = Microimage, AZ = AZ, H = Hitachi.

Positive electron resists are polymer chains in which chemical scission occurs upon exposure to the e-beam. The fractured chain has an average MW lower than the unexposed material, and may then be removed by developer without significantly attacking the unexposed areas. Successful implementation of this process, however, requires careful selection of solvents. The process engineer must find the best combination of solvents which results in the highest differential solubility ratio between the exposed and unexposed regions.

As with positive optical resists, positive electron beam resist development can be treated as an etching phenomenon. Figure 9a shows the resist profile of the most commonly used positive e-beam resist, poly(methylmethacrylate), or PMMA, for various develop times. To obtain a good profile, the etch rate of the exposed area should be maximized with respect to that of the unexposed areas. The resist solubility is characterized by the fragmented molecular weight of the exposed molecules, M_f , which in turn depends on the absorbed energy density in the resist, E . The dissolution rate, R , for exposed resist given by:

$$R = R_0 + \beta M_f^{-\gamma} \quad (3)$$

where R_0 is the removal rate of very high molecular weight materials (e.g. material in unexposed regions). M_f is found from:

$$M_f = (g E) / (\rho N_0) \quad (4)$$

and where: ρ is the resist density; N_0 is Avogadro's number; and g is the radiation yield (i.e. the number of scissions per eV of absorbed energy). Table 3 lists values of the relevant parameters (R_0 , α , and β) for some developers of PMMA resist. The parameter R_0 describes the removal

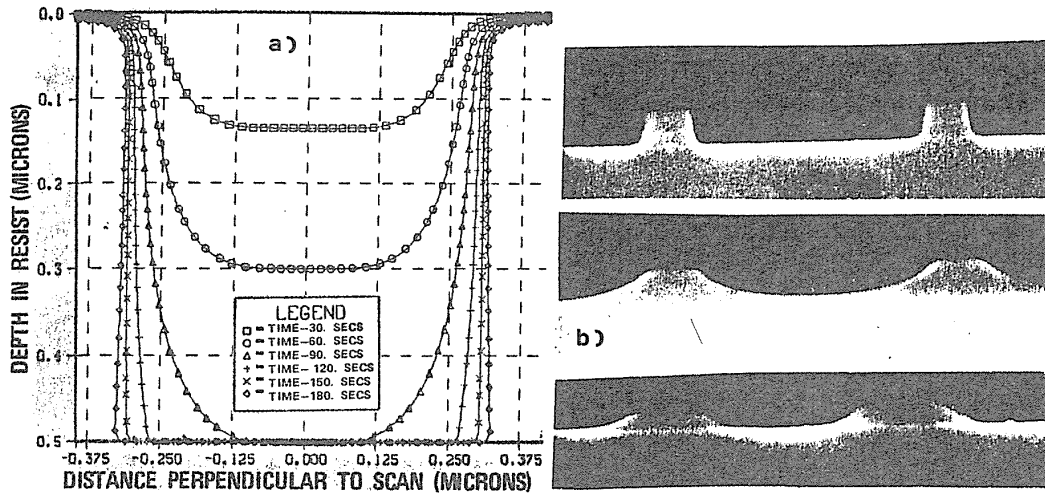


Fig. 9 (a) Developed contours at 30 s intervals at a nominal half micron exposure at 20 keV. Nominal development occurs at 120 s⁸. Reprinted with permission of Semiconductor International. (b) Effect of developer strength on line cross-sections and resulting resolution in a typical negative resist³². Reprinted with permission of the American Physical Society.

rate for resist of very high molecular weight (i.e. in the unexposed areas), and this rate should be as small as possible. The parameter γ represents the contrast of the resist. Note that its value should be as large as possible. As discussed in Chap. 12, higher contrast resists result in better resolution and critical dimension control. There is, however, a limit on increasing γ , since β also increases, and therefore the overall sensitivity of the resist decreases. The actual developed resist profile depends on: 1) the three-dimensional energy density distribution; 2) the amount of electron flux or exposure, in C/cm^2 ; and 3) the solubility rate of the resist /developer system. Significant effort is continuing to improve e-beam resists in terms of their sensitivity, resolution, adhesion to the substrate, and dry etch compatibility. Three review articles on recent developments in e-beam resist technology are given in the reference list^{10,11,12}.

The most widely used positive e-beam resist is PMMA, which has a sensitivity of $80 \mu C/cm^2$. The resolution of this resist is better than $500 \text{ \AA}$, since it does not swell. On the other hand, since it is ~ 100 times less sensitive, it requires exposures ~ 100 times longer than the negative resist, COP. Commercial products based on PMMA have improved the sensitivity of the original formulation, without losing its favorable dissolution properties (from $80 \mu C/cm^2$ to $15 - 30 \mu C/cm^2$). An alternative material, poly (butene-1-sulfone) has a high sensitivity ($\sim 2 \mu C/cm^2$ at 20 kV), but exhibits poor dry etch resistance and poorer resolution ($\sim 0.5 \mu m$).

Inorganic resists, consisting of GeSe (onto which AgSe is evaporated), can also be used for EBL. Upon irradiation, the Ag migrates into the GeSe layer to form a material that may be wet

Table 3. SOLUBILITY RATE PARAMETERS for PMMA at ROOM TEMPERATURE⁸

Developer	R_0 ($\text{\AA} / \text{min}$)	β	α
MIBK	84	3.14×10^8	1.5
1:1 MIBK:IPA	0	6.70×10^9	2.0
2:3 MIBK:IPA	0	9.37×10^{12}	2.75
1:3 MIBK:IPA	0	9.33×10^{19}	3.86

or dry developed. The resultant pattern in the resist forms a negative image. High resolution at a sensitivity of $100 \mu\text{C}/\text{cm}^2$ has reportedly been achieved.

Optical resists such as AZ 1350 can act as a positive or negative e-beam resist depending on the developer. Work also continues on dry developable resists, plasma developed resists, and self-developable (ablative) resists^{11,12}.

In order to predict post-development resist profiles, a *development model* must be coupled with the *exposure model* previously presented. For example, Fig. 9b shows the effect of developer strength on the developed image in COP resist. The 3:1 developer mixture develops the unexposed resist, but is not strong enough to remove the tail of the resist that was cross-linked by scattered electrons. The 4:1 developer mixture produces good images, while the 5:1 and 7:1 mixtures result in swelling of the resist (which in effect broadens the line). The broadening reduces resolution, and may result in bridging of adjacent features. This implies that tests must be conducted to determine the correct exposure /developer combination for a given e-beam resist to establish a reproducible process.

X-RAY LITHOGRAPHY

X-ray lithography is a process for imaging a full-field mask onto a wafer by using x-rays of very short wavelength (e.g. $4\text{-}50\text{\AA}$). At shorter wavelengths, transmission through the "opaque" mask regions is too great, while at longer wavelengths, transmission through the clear portions of the mask is too low. The ultra-short wavelengths eliminate the diffraction effects that limit the resolution of optical proximity systems. Although x-ray lithography was restricted to the research environment for a lengthy period, commercial x-ray systems have finally begun to become available¹⁴. A schematic of an x-ray lithography system is shown in Fig. 10.

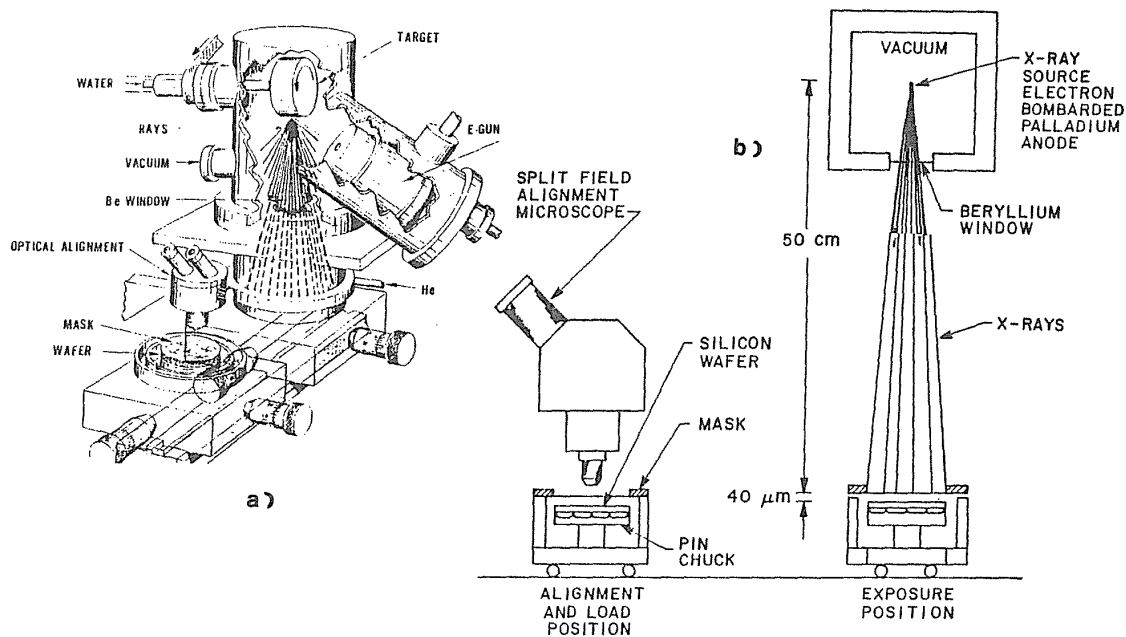


Fig. 10 (a) Line drawing of complete x-ray exposure system with alignment³⁰. (b) Schematic of an x-ray lithographic system³³ (©1983 IEEE). Reprinted by permission of American Phys. Soc.

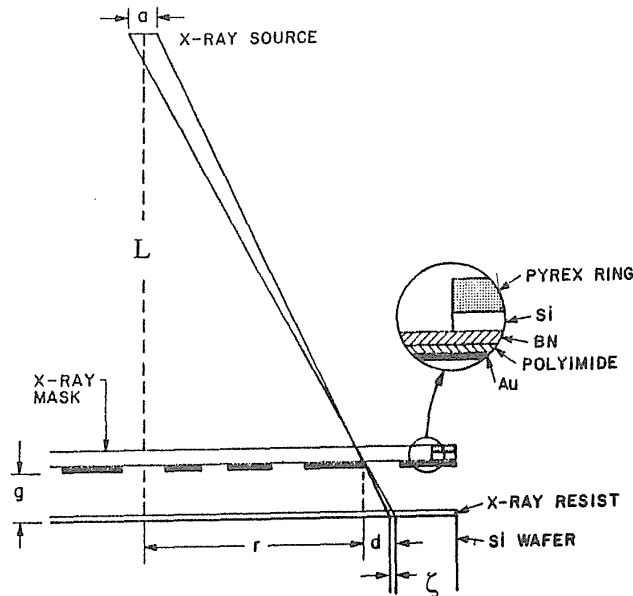


Fig. 11 Geometric effects in x-ray lithography. Insert shows x-ray mask³³. (© 1983 IEEE).

The major promise of x-ray lithography is its potential for attaining high resolution ($\sim 0.5 \mu\text{m}$) together with high throughput (e.g. 40-50 150 mm wafers /hr). The technology also offers the advantages of eliminating both the depth of focus problems, and the reflection and scattering effects that are associated with optical and e-beam lithography processes. X-rays also provide high aspect ratios in resist, and are immune to defects caused by organic particulates present on the mask (because x-rays in the 15-40 Å wavelength region are not appreciably absorbed by materials formed of low atomic number elements).

As x-rays are not capable of being focused into fine spots, the lithography process involves a form of shadow printing. As such, there are some geometrical effects associated with shadow printing that limit the resolution of x-ray lithography. For example, consider an x-ray source of diameter, a , at a distance, L , from the mask, and which is separated a distance, g , from the coated wafer as shown in Fig. 11. A *penumbral blur*, ζ , occurs on the resist image given by :

$$\zeta = (g / L) a \quad (5)$$

For a typical x-ray system, where a is 3 mm, g is 20 μm , and L is 26 cm, a ζ of 0.23 μm results. This effect can be tolerated if the intensity of the exposure in the blur is not decreased below the threshold intensity required for adequate exposure. In addition, the effect can in fact be advantageous, since, due to blurring, images of x-ray absorbing particles on the mask of $\sim 0.45 \mu\text{m}$ or smaller, will not be printed.

Another limiting geometrical effect is *lateral magnification error*, which results from x-ray divergence from a point source and the finite mask-wafer separation. The image on the wafer is shifted by an amount, d , given by:

$$d = (g / L) r \quad (6)$$

where r is the radial distance measured from the center of the wafer (Fig. 11). The error is zero at

the center of the wafer, but increases linearly with distance toward the edge. For large wafers this can result in *run-out* effects as large $5\text{ }\mu\text{m}$ near the edge of the wafer. Compensation for these errors can be achieved by adjusting image positions on the mask. The real problem is created as a result of non-flatness of the mask and the wafers. To avoid such problems, flatness for both masks and wafers must be held to better than $1\text{ }\mu\text{m}$. A way around maintaining such tight requirements is to reset the mask /substrate gap prior to each exposure. However, local distortions of the Si resulting from processing, do not allow the gap to be set equally over the entire wafer surface. For wafer diameters larger than 75 mm , step-and-repeat on the wafer would improve this condition. The practical use of step-and-repeat systems, however, requires that resists of with less than $1\text{ mJ}/\text{cm}^2$ sensitivity, and much brighter x-ray sources become available. The higher sensitivity resists and brighter sources would allow full wafer exposure systems to operate at a longer L, while still maintaining reasonable exposure times, thereby reducing both the penumbral blur and lateral magnification error. A last major technological hurdle that must be overcome before x-ray lithography can be considered for production process applications, is the *development of an effective mask fabrication technology*.

X-Ray Sources

X-ray tubes are the simplest x-ray sources. In such tubes, high energy electrons (e.g. 25 keV) are focused onto a metal (e.g. a palladium) target. X-rays (characteristic and background) are emitted with an efficiency of less than 1%, while the remainder of the energy goes into heating the target. The x-ray power produced is limited by the ability of the target to dissipate this heat. Such heating requires that the target be water-cooled. The most widely used x-ray tube design has an the inverted cone geometry¹⁵. This provides a large surface area with a minimum and symmetric projected spot size (Fig. 12). Sources of this type range from $4\text{--}7\text{ kW}$ in a 3 mm spot. By utilizing high velocity coolants, the heat transfer can be improved, and this allows targets to operate with power densities of $60\text{ kW}/\text{cm}^2$. Further enhancements to this technology may result in producing sources with 6 kW in a 1.5 mm spot. Such power densities are

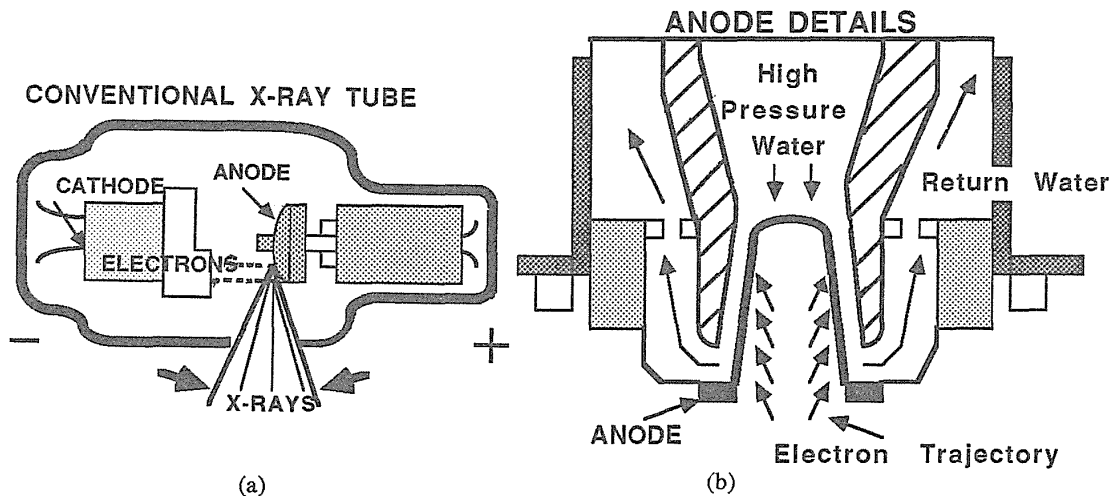


Fig. 12 (a) Conventional x-ray tube. (b) Stationary-anode x-ray tube uses a cone shaped target with bombarding electrons directed into the conical cavity³⁴. Reprinted with permission of Semiconductor International.

adequate for full wafer exposure, but not for step-and-repeat use.

The utilization of rotating anodes allows delivery of considerably higher power, but gradual decreases in output are observed as carbonaceous material deposits on the anode. This problem has been eliminated through the utilization of ferrofluidic seals. The complexity, cost, and spot size, however, are some of the remaining drawbacks of this technology.

An alternative approach to achieving high output x-ray sources is *synchrotron radiation*. Synchrotron radiation is emitted by electrons in response to their radial acceleration, while they are maintained in circular orbits within a storage ring or synchrotron. The x-rays from this device are nearly collimated (i.e. no geometrical effects) with flux densities in excess of 10-20 mW/cm² at the wafer plane. The radiation beam uniformity from this source is in the 10-50Å range, which is strongly absorbed by the thin absorber patterns of the x-ray masks (Au). The major disadvantage of the synchrotron source is cost, which may exceed \$10 million for a multiport system. Furthermore, if system problems caused all ports to be shut down, excessive downtime could make the operation of multiport systems extremely expensive.

A third approach is the use of *laser plasma sources*¹⁶. In these sources, either a pulsed IR laser or UV excimer laser is used, with pulse widths varying from 50 psec to 10 nsec. The beam is focused on the target, where it creates a plasma of sufficiently high temperature to produce continuous and characteristic x-ray radiation. A 12% conversion from laser power to useful x-rays has been obtained for Cu-L_α radiation, but the efficiency decreases with increasing Z of the target. The emitted energy density can be as high as 6.3 mW/cm², which is some 50 times brighter than electron impact sources. Another major advantage of this approach is that the power supply can reside in a remote location relative to the aligner, thus saving valuable clean room space and avoiding problems due to electromagnetic interference. Presently, work is being performed to increase the pulse repetition rate while reducing peak power, and to decrease the extent of debris deposited on the x-ray window by firing the laser in synchronism with a shutter. The debris is generated from target ablation as it is struck by the laser.

X-Ray Masks

The fabrication of suitable masks has always been, and continues to be, the most difficult challenge of x-ray lithography. The *mask blank* consists of a thin layer of x-ray absorbent material (usually gold), supported on a substrate. Note that in optical masks the absorber is a layer of chrome, and the substrate is glass. A variety of materials have been investigated to serve as the substrate for the absorber layer. The leading contender to emerge from the group is the multilayer structure consisting of boron nitride (BN) and polyimide. This structure was developed at Bell Laboratories¹⁷, and x-ray blanks using the technology are being commercially manufactured¹⁸. Such substrates provide good x-ray transmission, strength, inertness, and long term stability. Figure 13 outlines a set of processing steps involved in making such blanks for x-ray masks.

A silicon wafer is used as the starting material. The wafer is coated with BN by LPCVD techniques. The central area of the wafer backside is next etched back to silicon by plasma etching. The wafer is then bonded to a pyrex ring, and a polyimide coating is spun on the front side and cured. The polyimide surface is then sputter deposited with a multilayer metal (absorber) structure [e.g. Ta (300Å)/Au (6000Å)/Ta (800Å)]. The exposed silicon is then wet-chemically etched away, leaving the absorber and polyimide film, which constitute the mask blank.

A *subtractive process* can be used for pattern formation on the mask. A pattern is written using e-beam lithography into a photosensitive coating. The first Ta layer is etched by reactive ion etching, using a CF₄ plasma. The Au layer serves as an etch stop. The resist film

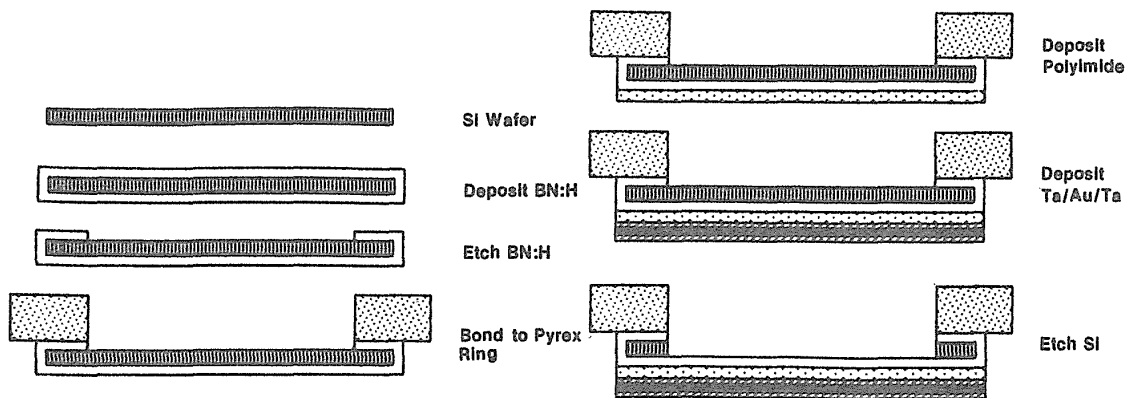


Fig. 13 X-ray mask blank processing sequence¹⁹. Reprinted with permission of Solid State Technology, published by Technical Publishing, a company of Dun & Bradstreet.

is then stripped, and the 800 Å Ta film serves as the mask for subsequent pattern transfer. The 6000Å Au layer is sputter etched or ion milled in an Ar-O₂ atmosphere. The O₂ is used to increase the selectivity of the etch, so that the Au etches more quickly than the Ta. The bottom 300Å Ta film serves as an etch stop to the Au etching, and also as an adhesion layer. The final step is to remove the Ta by reactive ion etch in a CF₄ plasma. The Au film serves to absorb the x-ray radiation in regions where it has not been etched away. A PMMA film then coats the mask to suppress photoelectron and Auger emission during exposure. The sputter etch process results in angles of the Au film of 65-73° because of *faceting* (see Chap. 10). As a result of this effect, the minimum line spacing in 0.6 μm Au films is limited to ~0.5 μm. This thereby limits the resolution of such masks. Reactive ion milling, or Ar/O₂ ion milling, can result in vertical sidewalls in the Au film, potentially allowing higher resolution masks.

Additive patterning (or *liftoff*) can also be used to produce Au lines with more vertical side-walls, thereby improving the resolution (Fig.14). This is achieved by the electroplating of Au through a vertically walled stencil. (See Chap. 15 for additional information on *Liftoff*.)

PMMA films 1.0 μm thick have been patterned with direct e-beam writing to produce 0.5 μm lines and spaces. Bilevel and tri-level processing techniques have been used to create high

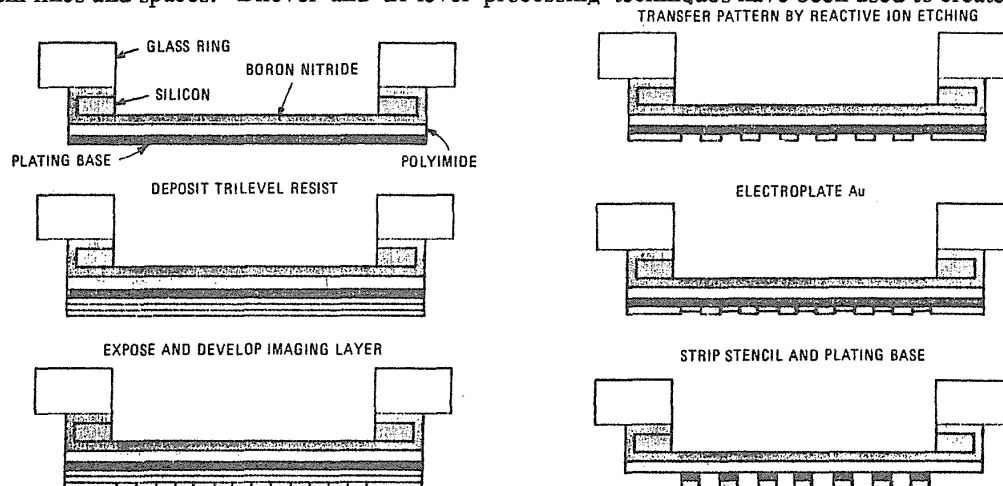


Fig. 14 Additive process for pattern formation on an x-ray mask¹⁹. Reprinted by permission of Solid State Technology, published by Technical Publishing, a company of Dun & Bradstreet.

resolution stencils. Tri-level processing has also met with considerable success in forming such stencils. A planarizing layer 1.2-1.5 μm thick, and a 750 $\text{\AA}$ Ta transfer layer (followed by a thin imaging resist) is now commercially available for making additive x-ray masks¹⁸. (See Chap. 12 for additional information on multilevel resist processing.) The plating base on which the electrodeposited Au grows typically consists of a 350 $\text{\AA}$ Ta top layer, which serves as a clean and flat Au base during the tri-level resist patterning. An initial 200 $\text{\AA}$ layer of Au is sputter deposited to provide the necessary conductive path during plating. The Ta layer serves as an adhesion layer between the Au base and the polyimide /BN membrane, since Au adheres very poorly to the polyimide /BN material. The Au is typically plated from commercially available solutions such as BBT 200 (from Sel-Rex Plating Systems). Low stress films are generally achieved during plating of the Au. After the stencil is removed by CF_4 etching, the mask is ready for use. Repair of x-ray mask defects is difficult. Excess material can be removed by focused ion beams, while pinholes require the use of laser activated CVD for selective deposition.

The Au x-ray absorber must possess adequate thickness to block the incident radiation in the desired locations. The thickness of the absorber layer causes the equal lines and spaces to be projected at oblique angles, and become asymmetric as the features are removed from the center of the mask. Thus, absorber layers should be restricted to their minimum effective thickness.

The alignment of subsequent layers in x-ray lithography generally utilizes optical techniques. In addition to x, y, and θ alignment, the mask-wafer gap must also be set correctly. Alignment techniques are discussed in Ref. 19. Values of 2σ misalignments of 0.3 μm over 100 mm wafers have been obtained. Since e-beam lithography is required for fabricating x-ray masks, improvements in resolution, image size control, and placement accuracy in e-beam technology will be required to realize the full potential of x-ray lithography.

X-Ray Resists

X-ray resists must satisfy contradictory requirements. That is, on one hand a high sensitivity to ionizing radiation is necessary for exposure speed, while on the other, good etch resistance in plasma environments is required after exposure²⁰. For conventional and pulsed plasma sources, very low x-ray fluxes (10-100 $\mu\text{W}/\text{cm}^2$) mandate the use extremely sensitive resists. With synchrotron sources, conventional electron, or photoresists can be utilized.

In order to formulate x-ray resists with higher sensitivity four approaches have been taken. They are: 1) incorporation of more highly absorbing groups; 2) use of more reactive groups; 3) use of higher molecular weight polymers; and 4) new formulations which exhibit amplification in the exposure or development steps. An attempt at incorporating all four of the above approaches has resulted in the development of a polymer named poly (2,3-dichloro-1-propyl-acrylate), which operates as a negative resist. It is mixed with COP for adhesion, and is termed DCOPA. This resist material is generally used with tri-level processing, and has a sensitivity of 14 mJ/cm^2 and a resolution of $\sim 0.8 \mu\text{m}$. The limit of resolution is due to resist swelling during development. The resist must also be exposed in a 0.3% oxygen in nitrogen ambient for optimum resolution. A new negative resist, which shows reduced swelling (called PSTTF)²¹, boasts a sensitivity of 50 mJ/cm^2 and 0.5 μm resolution at the Al K_α wavelength. It would be suitable for the x-rays output of plasma sources, but is still too slow for electron-impact sources.

In the positive resist realm, long exposure times are required for adequate exposure. Work by Wilson and Ito²² incorporated chemical amplification to increase sensitivity. During exposure, a catalytic group is formed which enhances the polymer cleavage. Resolution down to

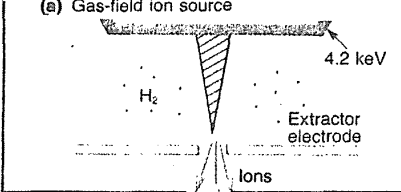
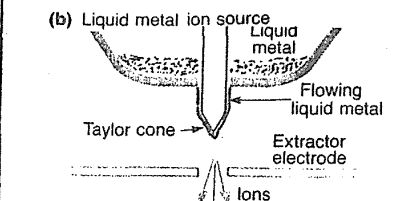
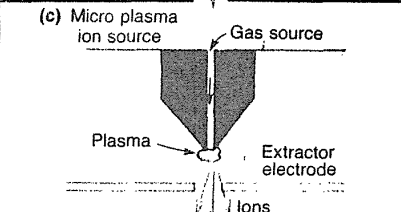
Source type & Schematic	General Source Characteristics	Brightness (β)	Energy spread	Angular current density	Virtual Size	Typical Ions
		($\text{A cm}^{-2} \text{sr}^{-1}$)	(ΔE) (eV)	(μAsr^{-1})		
(a) Gas-field ion source 		10^6	1	10-50 μAsr^{-1}	$\approx 10 \text{ \AA}$	H_2^+
(b) Liquid metal ion source 		10^6	5-10	10-50 μAsr^{-1}	100-500 $\text{\AA}$	Li Ga Au
(c) Micro plasma ion source 		10^3	5	3 mAsr^{-1}	50 μm	H He Ar

Fig. 15 Basic ion sources²⁴. Reprinted with permission of Semiconductor International.

0.5 μm has been achieved at x-ray doses approaching 10 mJ/cm^2 .

Work continues on developing new resists to support conventional electron bombardment sources. High sensitivity negative resists have been prepared but resolution is limited ($>0.75 \mu\text{m}$), and multi-level processing is required. The positive resists have low sensitivity, but outstanding resolution can be obtained with plasma or synchrotron sources.

ION BEAM LITHOGRAPHY

Ion beams can be used in the focused ion beam (FIB) and showered ion beam (SIB) modes²³. Etching, sputter deposition and ion implantation are all examples of processes that use SIB technology. Ion lithography and direct ion implantation are examples of FIB technology. The application of FIB to silicon processing is in its infancy, but significant research activity is continuing to be conducted at major corporate laboratories and universities in the U.S., Japan, and Europe in an attempt to capitalize on the potential advantages of this technique.

A typical FIB system (Fig. 15) consists of an ion source, a blanking system, deflectors to guide the beam over the wafer, and an electrostatic lens for imaging the beam-defining aperture over the wafer²⁴. The advantages of ion beams compared to electron beams are: a) since ions are more massive they are less prone to backscattering, and attendant resolution limiting proximity effects; and b) ion beam resists promise more sensitivity than e-beam resists. These advantages suggest that higher resolution limits are possible with ion beam lithography. On the other hand, since ion beam penetration in resist is only 300-5000 $\text{\AA}$, tri-level processing must be used.

A FIB system is characterized by its spot size, spot current, deflection frequency, field size, and writing speed. The larger mass of the ions limits focusing with an electrostatic lens, and

also produces lower deflection speeds than electron beam systems.

A major hurdle in this technology is the availability of reliable ion sources. Three types of sources are currently used: a) gas field sources; b) liquid metal sources; and c) plasma sources. *Gas field sources* show promise for ion lithography, *liquid metal sources* allow almost any ion to be used, and *plasma sources* can operate at high efficiency²⁴. Resist materials exhibit a higher sensitivity to ions than to either electrons or x-rays^{25,26}. For example organic polymers have from 10 to 100 times more sensitivity to ions than to electrons. The resolution of these resists, however, is limited by swelling, contrast, and low dose tails. Secondary electrons that are backscattered by ions have very low energies (~15eV) and ranges of only a few angstroms.

Submicron features have been exposed and developed in 0.25 μm thick substituted polystyrene films with focused 140-160 keV Si^+ beams, and the pattern transferred to the underlying layer. Inorganic resists such as GeSe_2 with a thin AgSe (~100 Å) surface layer can be exposed by low energy He^+ , N^+ , Ar^+ , Xe^+ and Ga^+ ions. A self developing (vapor development) resist (nitro-cellulose), has been described. Films of this material completely decompose when exposed to an ion beam above a certain dose threshold.

A potentially significant application of FIB technology is that of direct ion implantation, or doping without the use of masks or resists. This could eliminate many of the defect causing steps related to the doping process. Finer geometries are possible because the shadowing problems characteristic of broad-beam implantation through a mask can be eliminated. Other advantages could include: a) the production of lateral doping profiles; b) mixing of different types of devices on the same wafer; and c) low temperature annealing characteristics resulting from the high current densities associated with the beam. The main drawback of the technology is the low throughput (~1% of broad beam ion implantation), and low reliability of liquid metal sources.

Another useful application of ion beam technology is the repair of optical and x-ray masks. Opaque defects can be removed by sputtering away excess metal, while clear defects can be eliminated by etching a fine diffraction pattern into the mask (thereby rendering that region opaque).

The use of showered ion beam (SIB) lithography has taken two approaches. In the first, a broad ion beam illuminates a metal foil mask. The beam is then demagnified by a factor of 10, and projected onto and stepped across the wafer. In the second approach, a 3-6 μm thick <110> silicon membrane, with 1000 Å patterns, is used as the mask. The resist-coated substrate is exposed through the silicon foil using a collimated He^+ beam. The technique utilizes the dechanneling effect of the thin Au layers, as well as the difference in energy loss for the random and channeling directions.

REFERENCES

1. A. Carroll, J. Freyer, "Measuring the Performance of the AEBLE-150", *Proc. SPIE, Electron-Beam X-Ray & Ion Beam Techniques for Submicron Lithography IV*, Vol. 537, 1985, p. 25.
2. D.R. Herriot, "Electron-Beam Lithography Machines", in G.R. Brewer, (ed.), *Electron-Beam Technology in Microelectronic Fabrication*, Academic Press, New York, 1980.
3. W.R. Livesay, *et al*, "A Process-Compatible Electron Beam Direct Write System", *Solid State Technology*, Sept. '83, p. 137.
4. A.N. Broers, "The Submicron Lithography Labyrinth", *Solid State Technol.*, June '85, p. 119.
5. H.C. Pfeiffer, "Direct Write Electron Beam Lithography - A Production Line Reality", *Solid State Technology*, Sept. '84, p. 223.
6. A.D. Weiss, "E-beam Lithography: A Story of Dual Identities", *Semi. Intl.*, Feb. '84, p. 54.
7. L.F. Thompson and M. Bowden, "Lithographic Process: The Physics", in L.F. Thompson, C.G. Wilson, and M.J. Bowden, Eds., *Introduction to Microlithography*, ACS Symposium

- Series No. 219, American Chemical Society, Washington, D.C., 1983, Chap. 1.
8. J.S. Greenreich, "Process Hurdles in Electron-Beam Exposure of Sub-Micron Patterns", *Semiconductor International*, April '81, p. 159.
 9. J.S. Greenreich, *Proc. 9th Intl. Conf. Electron and Ion Beam Sci. and Technol.*; ed. Bakish, Electrochem. Soc., Pennington, N.J. (1980), p. 282.
 10. M.P.C. Watts, "Electron Beam Resist Systems", *Solid-State Technol.*, Feb. '84, III.
 11. E. Roberts, "Recent Developments in Electron Resists", *Solid-State Technol.*, June '84, p. 135.
 12. Y. Takahashi, "Evaluation of Commercial E-Beam Resists in Japan", *Semicon. Int'l.* Dec 84 p91
 13. R.K. Watts, "Electron Beam Lithography", in N.G. Einspruch, Ed., *VLSI Handbook*, Academic Press, Orlando, Fla., 1985, Chap. 20, p. 351.
 14. P. Burggraaf, "X-Ray Lithography & Mask Technology", *Semiconductor Int'l.*, Apr. '85, p. 92.
 15. J.R. Maldonado, *et al.*, *J. Vac. Sci. Technol.*, **16**, 1942 (1979).
 16. R. Byer, *et al.*, *Proc. SPIE*, Vol. 448, p. 2 (1983).
 17. D. Maydan, *et al.*, *J. Vac. Sci. Technol.*, **16**, 6 (1979).
 18. A.P. Neukermans, "Current Status of X-Ray Lithography" *Solid State Technology*, Part 1, Sept. '84, p. 185, Part II, Nov. '84, p. 213.
 19. A.R. Shimkunas "Advances in X-Ray Mask Technology", *Solid State Technol.*, Sept'84, p. 192.
 20. G.N. Taylor, "X-Ray Resist Trends", *Solid State Technology*, June '84, p. 124.
 21. F.B. Kaufman, *et al.*, Preprints, *ACS Div. Org. Coatings and Plastic Chem.*, **43**, p.375 (1980).
 22. H. Ito and C.G. Wilson, *Polymer Engrg. and Science*, Vol. 23.
 23. I. Brodie and J.J. Muray, *The Physics of Microfabrication*, Plenum Publ. Co., New York 1983.
 24. J.J. Muray, "Physics of Ion Beam Wafer Processing", *Semiconductor Int'l.*, April '84, p. 130.
 25. J.E. Jensen, "Ion Beam Resists", *Solid State Technol.*, June '84, p. 145.
 26. M.K. Shearer and G. Cogswell, "Focused Ion Beam Technology: Reviewing Applications Research", *Semi. Int'l.*, April '84, p. 145.
 27. "A New Mask Could Finally Open Up X-Ray Lithography", *Electronics*, Sept 16, 1985, p. 48.
 28. R.D. Moore, "EL Systems", *Solid State Technol.*, Sept. '83, p. 127.
 29. B.P. Pywczyk and A.E. Williams, "High Throughput Variable Shaped Electron Beam Lithography", *Solid State Technol.*, Sept. '83, p. 145.
 30. D. Maydan, "X-Ray Lithography for Microfabrication", *J.Vac.Sci. Technol.* **17**, 1164 (1980).
 31. D. Kyser and K. Murata, "Monte Carlo Simulation of E-Beam Scattering and Energy Loss", *Proc. 6th Intl. Conf. on Electron and Ion Beam Science*, 1974, Electrochem. Soc.
 32. E.D. Feit, *et al.*, *J. Vac. Sci. and Technol.*, **16**, 391, (1979).
 33. M.P. Lepselter, *et al.*, "A System Approach to 1- μ m NMOS", *Proc. IEEE*, **71**, 640, (1983).
 34. S. Harrell, "X-Ray Source Technology for Microlithography", *Semi. Int'l.*, Sept. '83, p. 74.

PROBLEMS

1. Calculate the number of electrons that must impinge upon each pixel if the minimum pixel dimension is $0.5\ \mu\text{m} \times 0.5\ \mu\text{m}$, and the electron resist being used is (a) COP, and (b) PMMA (see Table 2).
2. Explain why a shaped beam promises higher throughput than a Gaussian beam in e-beam lithography.
3. Explain how a *butting error* arises in electron beam lithography.
4. Explain why point C in Fig. 8 is not completely exposed, thereby causing the pattern in the beam resist to be smaller than desired at that point. Explain how intra-proximity effects can cause the space between metal lines patterned with a positive e-beam resist to be smaller than the

dimension specified in the design.

5. Explain how the penumbral blur in x-ray lithography causes even x-ray absorbing particles present on the mask, with a size of $<2X$ the penumbral blur value, not to be printed.
6. Elaborate on the problem of *run out* that can occur in x-ray lithography. That is, explain why it arises, and give techniques that could reduce its effects.
7. What are the main factors that limit the resolution in x-ray lithography? In addition to resolution, explain why alignment in x-ray lithography is difficult. (i.e. How is alignment performed in x-ray lithography?)
8. Advances in e-beam, x-ray, and ion beam lithography will improve the capabilities of these processes beyond those reported in this text, as time goes on. Thus, it is valid to ask the reader to determine the state-of-the-art performance specifications of these techniques at the time this problem is assigned.