X-RAY LITHOGRAPHY

X-ray lithography is a method used in electronic manufacturing to record a binary image (pattern) in a layer of photosensitive material spun on the surface of a semiconductor wafer. This method differs from other lithography techniques in the use of X rays with wavelength around 1 nm as recording radiation.

X-ray lithography (XRL) was invented at the Massachusetts Institute of Technology (MIT) by H. I. Smith in the 1970s (1). At the time, semiconductor fabrication employed a method of "contact lithography" to form the patterns on the semiconductor substrate used in the planar fabrication method. In this method, ultraviolet (UV) light is shone through a photographic glass slide (mask) with the pattern to be transferred to the substrate; light transmitted by the clear area exposes the photosensitive film on the wafer. The maximum resolution is determined by the diffraction of the UV light through the mask features and into the recording material; typically, it is difficult to expose features smaller than 1 μm. To avoid defects caused by the contact between mask and substrate, H. I. Smith proposed to separate the two and use a much shorter wavelength to avoid excessive blur caused by the diffraction of the UV light, as illustrated in Fig. 1. The invention was ahead of its time, and the development of optical projection lithography steered the industry in other directions.

Today, as the dimensions that are patterned on the wafers approach and eventually enter the 100 nm region, it becomes progressively harder and harder to use optical lithography to define those structures. X-ray lithography has continued to evolve, addressing smaller and smaller dimensions. When optical lithography will eventually be unable to pattern smaller linewidth features, X-ray lithography is one of the most promising techniques for its replacement.

X rays are electromagnetic radiation of very high energy and correspondingly short wavelength. For lithography applications, the best energy lies in the spectral region around 1 nm. No optics exist that can focus X rays of this wavelength to the degree of accuracy required by lithography, and thus only direct replication (often referred to as 1× imaging) is possible. The selection of this energy range is dictated by several factors, illustrated in Fig. 2. First and foremost, we must remember that lithography is an industrial manufacturing process and, as such, must sustain a high volume of production. This implies that enough power must be delivered to the resist in order to expose it in a short time (typically 50 mJ/cm^2 to 100 mJ/cm^2 in less than 1 s). A source of X rays such as a synchrotron produces enough power to satisfy this requirement, and it displays a smooth spectrum of radiation. The X rays are then relayed to the mask by a transport system called a "beamline," a specialized optical system containing one or more grazing incidence mirrors. The mask is formed by a material transparent to the X rays coated with a patterned absorber. In the clear areas, the X rays are transmitted and are absorbed in the resist. Thus, the "optics" used in this method must satisfy at the same time the following:

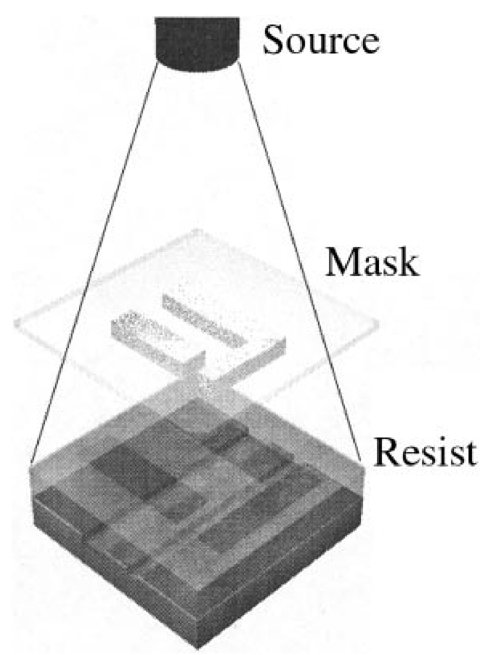

Figure 1. Schematic of an X-ray lithography system. A source of X rays illuminates the mask, and the transmitted radiation exposes the photoresist.

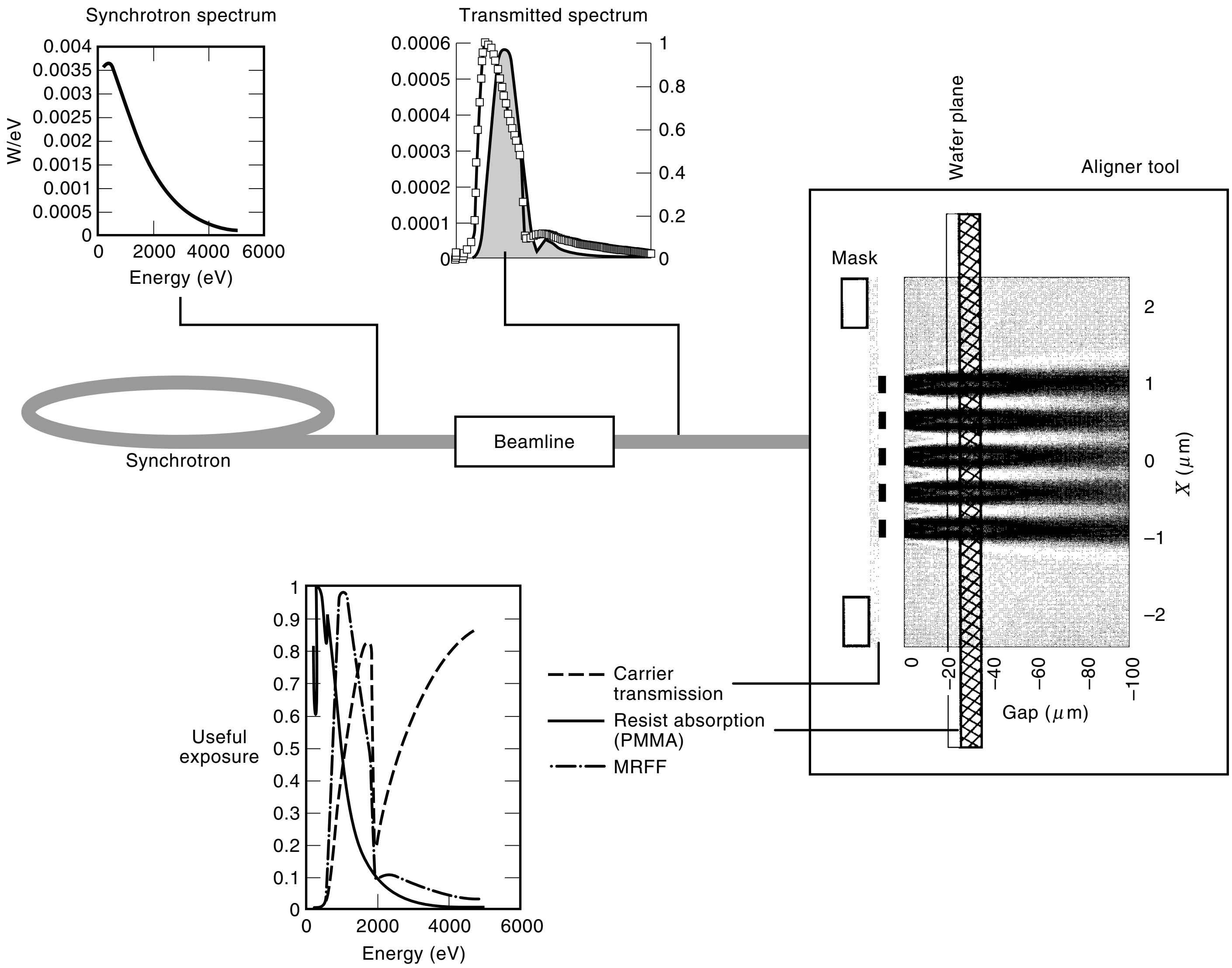

Figure 2. XRL system.

- The mask substrate must be transparent to X rays with $T \geq 50\%$; typically, harder X rays are transmitted better.
- The absorber must attenuate about 5 to 10 times the radiation to provide an image with good contrast; at harder X rays, the contrast decreases.
- The photoresist must absorb at least 10% of the radiation; harder X rays are absorbed less and thus are less effective in exposing the photoresist.

These requirements are contradictory, and a compromise region must be found. By multiplying the transmission of the mask by the absorption of the photoresist, as shown in Fig. 2 we can define a region of spectrum [mask-resist filter function (MRFF)] where the best compromise is achieved. This region happens to be centered around 1 nm, as it is evident from the figure: X rays of wavelength shorter than 1 nm are not absorbed well by the photoresist, and longer wavelengths are not transmitted by the mask.

Thus, in an XRL system the radiation is filtered and delivered to the mask with a spectrum similar to that shown in Fig. 2. When the X rays illuminate the mask part of the radiation is stopped in the patterned absorber, and part is transmitted. In first approximation, the image formed is simply the shadow cast by the absorber when illuminated by the X-ray beam. Because of the wave nature of the radiation, *diffraction* will be observed; that is, the radiation will tend to spread out from the areas illuminated. This is again shown in Fig. 2, where the right panel shows the intensity of the X-ray beam after it leaves the mask. We can easily observe how the pattern is clearly defined over a distance of several tens of microns before becoming too blurred to be useful for delineating binary features.

At wavelengths around 1 nm, there is relatively little diffraction because the size of the features in the pattern are much larger than the wavelength. The extent of diffraction of a radiation of wavelength λ from a feature of size W under propagation through a distance g can be quantified by using

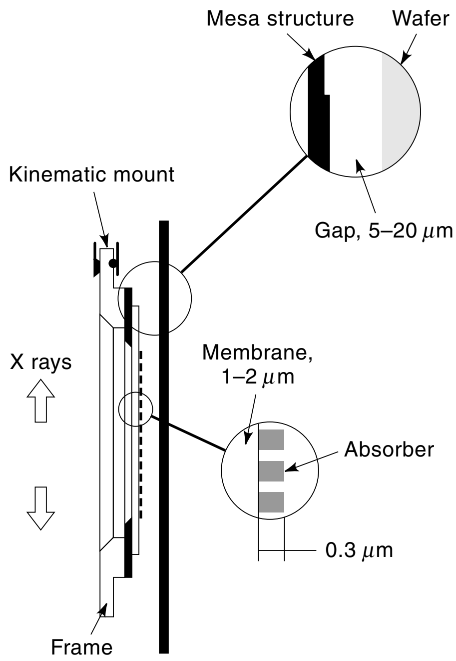

Figure 3. Detail of exposure system.

the *Fresnel number,* defined as

$$f_{\#} = \frac{W^2}{\lambda g}$$

If $f_{\#} \gg 1$, then the amount of diffraction is relatively little, and the image is essentially a shadow casting process; it becomes significant at $f_{\#} \leq 1$. We can summarize the *patterning ability* of X-ray lithography by using the Fresnel number as a figure of merit. In lithography, we can somewhat alter the pattern on the mask in order to deliver an image that reflects our desired shape. Thus, in optical lithography we can pattern features that appear to be beyond the resolving power of the optical system. In XRL, by carefully optimizing the mask design we can deliver very high resolution and large depth of focus, the two key parameters of a lithographic system.

An X-ray lithography system is complex, and it includes several parts. The source used today is typically an electron storage ring (ESR), a form of high-energy accelerator where electrons are kept moving on a near-circular orbit at a speed approaching that of light. Their energy is around 0.5 GeV to 1 GeV, and the size of the accelerator designed for these applications is relatively small (about 4 m by 10 m). In these conditions, the electrons generate a large amount of radiated power with a median energy around 1 nm. ESRs are very effective sources of X ray because they are essentially dipole antennas, emitting at the Larmor frequency of the electron revolution along the orbit; it is the relativistic Lorentz contraction due to the high electron speed that shifts the spectrum from the microwaves to the soft X rays. ESRs generate several kilowatts of X rays.

The key element of the X-ray lithography system is the mask. It is fabricated using a thin silicon carbide membrane (1 μm to 2 μm thick), onto which an absorber such as W, Ta, or TaSi (0.3 μm to 0.5 μm thick) is deposited by sputtering and then patterned (Fig. 3). The mask itself is patterned using electron-beam lithography, and then the pattern is etched into the metal film using a form of reactive ion etching. A finished mask is shown in Fig. 4; the patterned area is 25 $\times$ 25 mm^2.

X-ray masks are quite challenging to manufacture, mainly because of the exacting requirements on the accuracy of the pattern placement. Since each new exposure must register exactly with the previous structures already formed on the wafer, the margin for error is minuscule: For 0.13 μm structures, the mask placement accuracy must be better than 0.014 μm.

The image projected by the mask is recorded in the *photoresist* (or resist for short), a polymeric material coated on the wafer. The resist becomes soluble in a developer, and is removed by it, where it is exposed (positive resist). The undissolved patterned material thus protects a portion of the wafer from the following processing step. The resists are typically polyhydroxystyrene-based, and they have the same ingredients as those used in optical lithography; however, they are reformulated in order to improve their sensitivity in the X rays to values smaller than 100 mJ/cm^2.

The mask and the wafer are aligned to each other and held in position by a *stepper,* an exposure machine capable of performing multiple exposures. The pattern size, or exposure field, of an X-ray mask can be as large as 50 $\times$ 50 mm^2, but silicon wafers used today in industry are 200 mm in diameter, to soon become 300 mm. Hence, the exposure tool repeats several exposures (or prints) of the mask over the wafer, stepping from position to position. A type of X-ray stepper is shown in Fig. 5. Contrary to the case of optical lithography, no complicated and expensive lens is required to form the image. The process relies exclusively on the short wavelength of the radiation and on the high-resolution mask to form the image. Several experimental steppers are available at the time of writing.

Alignment between mask and wafer is performed by detecting the relative position of complementary *alignment marks* located on the mask itself and on the wafer. There are

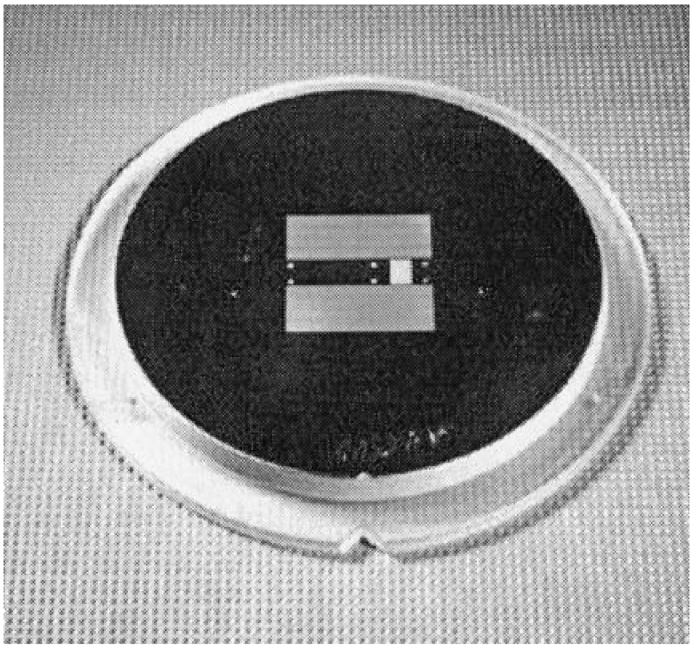

Figure 4. An IBM X-ray mask.

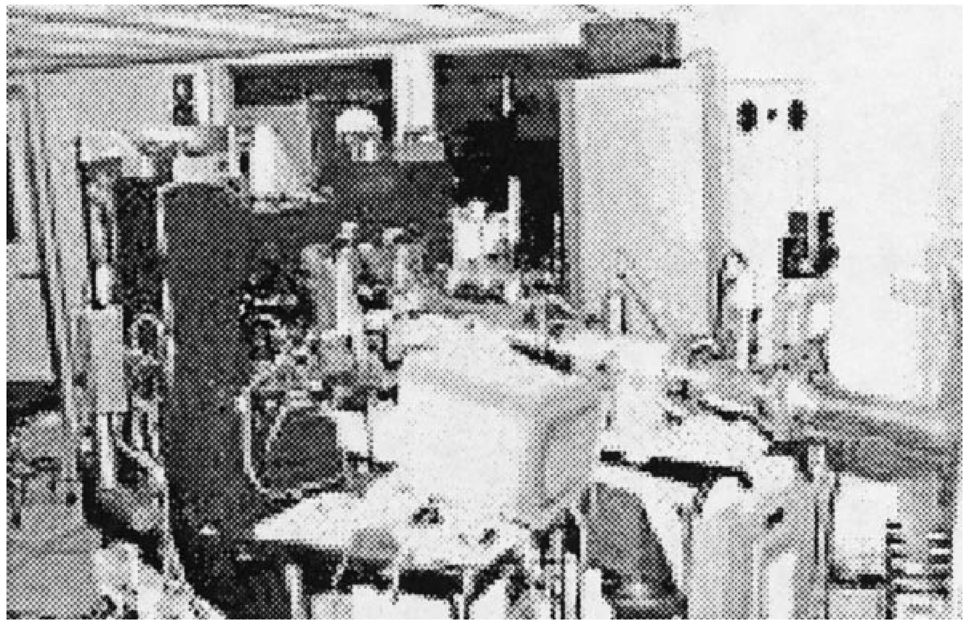

Figure 5. The SAL XRS-200/4 X-ray stepper installed at the University of Wisconsin. The X rays are incoming along the beamline to the right of the tool.

many different types of alignment marks detection schemes; all are based on the use of optical wavelengths. The marks locations can be directly imaged using simple optical microscopes (SAL), or detected from the phase of the laser beam diffracted by two set of gratings on mask and wafer (NTT), by imaging the Moiré fringes from superposed gratings (MIT); these optical methods require that the marks on the wafer to be imaged through the membrane (TTM). Of course, all TTM methods require transparent membranes, and this may sometimes be a problem. Indirect, or off-axis, methods have been also developed to eliminate this problem: Two independent imaging systems are located on the mask and wafer stage, and they are used to map the location of the marks of the complementary part (SVGL). The coordinates are then stored in a computer memory, defining two virtual grids: the mask as seen from the wafer, and the wafer as seen from the mask. A common reference point is established thanks to an X-ray sensor. This method has the advantage that the mask does not need to be transparent to the alignment wavelength.

Optical lithography is the dominant force in the semiconductor industry today, and it will remain so until difficulty in delivering a reliable and cost-effective process will force the switch to an alternate technology. At the time of writing, it is still unclear when this transition will occur. Following the SIA Roadmap (2), the 2001 180 nm node (i.e., device generation) will be manufactured using deep UV optical lithography (248 nm KrF laser wavelength) and the 2004 130 nm node with a combination of 248 nm and 193 nm (ArF laser). The situation is much less clear for the 100 nm generation, and it may also be different for the memory and microprocessor markets. In any case, the development of X-ray lithography was very aggressive in the early 1990s but slowed down considerably toward the end of the decade, as alternative technologies were also beginning to be considered (SCALPEL, EUV, ion beams). While it is technologically the most mature of the various alternative lithographies (3), the development of a suitable 1× mask has hampered the acceptance of the technology. In the United States, IBM has been and remains the largest proponent of X-ray lithography; in Japan, several companies are developing the technology either on their own (Mitsubishi, NTT) or as part of a large consortium (ASET). Programs exist also in Síngapore, South Korea and Europe (France and Italy). Both in the United States and Japan, considerable government support has been directed to the development of X-ray lithography.

For an in-depth discussion of the technology, see Ref. (3). E. Spiller (4) and A. Wilson (5) present a very interesting historical perspective on the development of X-ray lithography, while S. Hector (6) and J. Silverman (7) present some recent developments in X-ray lithography practiced in the U.S. industry.

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