

# DEVELOPING A SOFT X-RAY PROJECTION LITHOGRAPHY TOOL

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The circuit-integration densities needed for semiconductor devices in the late 1990s will require advanced patterning technologies that can print line widths of 0.2 micrometers or less. Because it uses shorter wavelengths, X-ray lithography is one of the most promising methods for volume production of such circuits. X-ray projection lithography, which uses reflective optics, offers the added advantage of image reduction. AT&T Bell Laboratories has used X-ray projection lithography for diffraction-limited imaging with 140-angstrom radiation from a synchrotron. Now, Sandia National Laboratories and AT&T Bell Laboratories are developing a soft X-ray projection lithography tool that uses a compact source of X-rays: the laser-plasma source. A possible alternative to the expensive, complex synchrotrons, the laser-plasma source could influence the future commercialization of X-ray projection lithography. This paper describes soft X-ray projection lithography and our progress in combining projection optics at 140 angstroms with a laser-plasma source.

## Introduction

A unifying theme in the rapidly evolving microelectronics business is the push to pack more and more circuit elements into smaller and smaller devices. The driving force for higher density chips comes principally from the computer industry, whose customers put top priority on high-performance microprocessors and memories. Consumers want more powerful systems that operate faster, contain more memory, and occupy less space.

It is in the fabrication of memory chips, such as DRAMS (dynamic random-access memories), that the current manufacturing technology is being pushed to its limit. Today, commercial 4-Mbyte

### Panel 1. Acronyms, Symbols, and Terms

ablation crater — hole or pit created when a laser pulse impinges on a surface and ablates (vaporizes) some material

blackbody — a term given to describe the absorption and emission characteristics of an object

condenser — a mirror or system of mirrors

$d$  — distance between periodic layers

deep UV — deep ultraviolet

DOF — depth of field of a camera

DRAM — dynamic random-access memory

$\theta$  — angle of incidence

hard X-rays — X-rays of shorter wavelength (roughly, 50Å to 0.12Å) that penetrate more deeply than soft X-rays. They are used for medical procedures, such as chest or dental X-rays.

i-line — the shortest usable wavelength of light from a mercury lamp, i.e., 0.365  $\mu\text{m}$

KrF — krypton fluoride

$\lambda$  — wavelength of the light entering the camera

LSM — layered synthetic materials

LPS — laser-plasma source

Mo/Si — layered molybdenum and silicon

$n$  — an integer

NA — numerical aperture; the acceptance angle over which light is admitted into the camera

objective — a camera composed of several mirrors

$R$  — resolution of the camera

Si — silicon

Si/Ge — layered silicon and germanium

soft X-rays — X-rays with the longest wavelength (roughly, 250Å and 50Å) and, therefore, lowest energy. They penetrate only a few tens of micrometers into most materials.

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(megabyte) chips have minimum feature sizes of 0.8  $\mu\text{m}$  (micrometers); 1  $\mu\text{m}$  is about 1/100th the width of a human hair. By the year 2000, new manufacturing techniques will be needed for memory devices as large as 1 Gbyte (gigabyte) with minimum feature sizes of 0.18  $\mu\text{m}$  or less. *Lithography*, the process of transferring circuit patterns onto a silicon wafer, is a key technology that must be developed further to achieve that goal.

As this paper describes, AT&T Bell Laboratories and Sandia National Laboratories are collaborating to develop a new lithographic tool that is based on the concept of soft X-ray projection lithography (SXPL). This tool will enable us to manufacture chips with extremely high densities during the latter half of this decade. As in any highly competitive industry, the first semiconductor manufacturers to achieve this capability will dominate the lucrative, worldwide, microelectronics market. To develop the lithographic tool as rapidly as possible, we have combined the imaging and device-processing expertise at AT&T Bell Laboratories with the soft X-ray sources and systems engineering at Sandia. (Panel 1 defines acronyms, symbols, and terms used in this paper.)

From a practical or manufacturing viewpoint, the ideal lithographic technology for the future should have at least these key attributes:

1. From a technical perspective, its performance must be equal to or better than competing technologies.
2. The technology should be less expensive than the competition's to implement and should be able to produce a product at a profit.
3. It should be ready and completely proven when the industry's need arises (preferably, not too much sooner and, certainly, not later).
4. From a marketing or insertion perspective, it should be, if possible, an extension of the current technology. If not, it should be a direct replacement for existing technology in manufacturing facilities. [By *insertion*, we mean the process of replacing the old lithographic equipment (i.e., the tool) with the new.]

The fourth characteristic, part of what we sometimes refer to as granularity, is a major "Achilles heel" for proximity X-ray lithography that is based on synchrotron-radiation sources.

*Granularity* is a term used by the technical community to reflect interdependency in a large instrumentation. For example, when a synchrotron-radiation source is used, many (a dozen or more) exposure stations are arranged around, and fed by, the synchrotron-radiation source. If the synchrotron-radiation source fails, then all the exposure stations become inoperable. Thus, if

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synchrotron-radiation sources are implemented, this will represent a major change in the way that manufacturing lines are set up. Currently, each exposure station on a manufacturing line is fed by its own, independent "light bulb." Therefore, if one exposure station goes down, it has no effect on the others; they continue to produce the product.

*Proximity X-ray lithography* is a one-to-one shadow printing approach being pursued by many groups around the world. It uses hard X-rays of roughly 10Å (angstroms), produced by a synchrotron-radiation source (the approach preferred by most groups) or a laser-plasma source, an approach we discuss later in this paper. (An angstrom is equal to one ten-billionth of a meter.) These X-rays pass through a mask, whose opaque regions correspond to the pattern being printed.<sup>1</sup>

*Synchrotron-radiation sources* consist of ultrahigh-vacuum storage rings where electrons that move at relativistic speeds are made to follow roughly circular orbits by high magnetic fields. As the electrons are bent, they give off electromagnetic radiation in a direction tangential to their path.

Even the new, "compact" synchrotron-radiation sources are relatively large. For example, the footprint of an optical lithography tool in use today is roughly 10 feet by 10 feet. Synchrotron-radiation sources that use normal magnets tend to be roughly 100 feet or more in diameter, depending on the energy of the electrons (and, hence, synchrotron radiation). The sources are extremely complex and require sophisticated electronics, ultrahigh-vacuum technology, and radiation shielding. In addition, the technical expertise required to run such sources does not exist on present-day integrated-circuit fabrication lines.

New machine designs are being developed that will use superconducting magnets to maintain the electrons on orbit. Although these machines will be more compact (about 25 feet by 25 feet), they must still be surrounded by thick walls of radiation shielding to protect workers. A synchrotron cannot be ordered and just

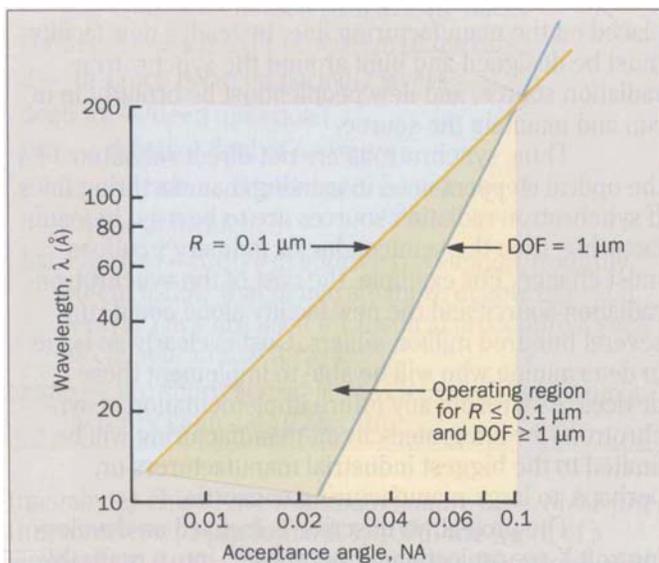
placed on the manufacturing line. Instead, a new facility must be designed and built around the synchrotron-radiation source, and new people must be brought in to run and maintain the source.

Thus, synchrotrons are not direct substitutes for the optical steppers used in existing manufacturing lines. If synchrotron-radiation sources are to be used in manufacturing, then the semiconductor industry's culture must change. For example, the cost of the synchrotron-radiation source and the new facility alone could run several hundred million dollars. Cost is clearly an issue in determining who will be able to implement these devices. As a result, any future implementation of synchrotrons for integrated-circuit manufacturing will be limited to the biggest industrial manufacturers or, perhaps, to large manufacturing consortia.

The project we describe is focused on developing soft X-ray projection lithography<sup>2,3</sup> into a realizable commercial tool by the end of this decade. AT&T Bell Laboratories has already shown<sup>4</sup> that SXPL can produce 0.05- $\mu\text{m}$  features.

SXPL is an image-reduction method and uses soft, rather than hard, X-rays. [*Soft X-rays* are those with the longest wavelength (i.e., lowest energy) and penetrate only a few tens of micrometers into most materials. *Hard X-rays* have shorter wavelengths and penetrate more deeply. They are used for medical procedures, such as chest or dental X-rays. Roughly speaking, the range for soft X-rays lies between 250Å and 50Å. The hard X-ray region spans roughly 50Å to 0.12Å.]

The image-reduction approach allows us to use masks that have large feature sizes and, thus, are easy to fabricate. In addition, these can be reflective masks that are written on thick, robust substrates and, therefore, will not distort or change characteristics during exposure. From a source perspective, the use of soft X-rays is a further advantage. Soft X-rays can be obtained readily from compact, laser-plasma sources (LPSS), which eliminates the need for synchrotrons and, potentially, lowers the barrier to technology insertion.



**Figure 1.** The tradeoff between resolution  $R$  and depth of field DOF when choosing the working wavelength  $\lambda$  and acceptance angle NA. For our camera system, the desired resolution is at least  $0.1 \mu\text{m}$  with a DOF of more than  $1 \mu\text{m}$ . Thus, points that fall within the operating region would satisfy both requirements. To obtain the largest NA possible, we must use a working wavelength of about  $140\text{\AA}$ .

### Projection Lithography

*Photolithography* is a process that uses visible light to transfer circuit patterns onto silicon chips, much like exposing a negative onto photographic film. Today, photolithography uses complex lens systems that reduce and transfer the image from a mask onto a silicon wafer. For example, in producing 4-Mbyte DRAMs, the pattern on a chrome-on-glass mask undergoes a 5:1 reduction, using light from a high-intensity mercury lamp.

**Current Limitations.** For years, experts have questioned whether photolithography could achieve the smaller feature sizes needed for the next-generation

memory devices. Despite their pessimism, optical lithography has progressed steadily and continues to be used for ever decreasing feature sizes. But eventually, feature sizes will need to shrink to dimensions smaller than the wavelength of the light used to produce them. That will present a problem—one that has been described graphically as trying to paint a thin line with a wide brush.

For example, the 4-Mbyte DRAM requires line widths of  $0.7$  to  $0.8 \mu\text{m}$ . The shortest usable wavelength of light from a mercury lamp, designated the *i-line*, is  $0.365 \mu\text{m}$ . While this is adequate for 4-Mbyte DRAMs, it cannot be used to produce 1-Gbyte memory chips, which will require line widths of about  $0.18 \mu\text{m}$ .

An obvious solution to this problem is to use light of shorter and shorter wavelengths. That is, we would start with wavelengths in the deep-ultraviolet (deep UV) region of the electromagnetic spectrum, and move down into the soft X-ray region and, finally, into the hard X-ray region.

Other possible approaches include direct-write techniques that use finely focused electron or ion beams. But these techniques “write” in a serial mode (which is slow), so they are not well suited to volume production.

Other approaches—projection electron-beam lithography, proximity X-ray lithography, and deep-UV lithography using phase-shift masks—are also being considered for advanced chip production. Our X-ray projection technique is an image-reduction method that uses all-reflective optics and soft X-rays.

**Soft X-ray Projection Lithography.** Let us describe, in general terms, the design requirements of any optical or X-ray projection lithography system.

To be useful for lithographic applications, a high-resolution system must preserve its focus over an adequate distance. In camera terminology, this means it must have enough depth of field, or DOF. The topology on a chip has a depth of about  $1 \mu\text{m}$ . Thus, for semiconductor manufacturing, an exposure system (regardless of its resolution) must have a DOF of at least  $1 \mu\text{m}$ .

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Whether a camera is working in the soft X-ray or visible-light region, its resolution  $R$  depends on the wavelength  $\lambda$  of the light and the acceptance angle NA (numerical aperture) over which the light is admitted into the camera. Their relationship is given by:

$$R = \frac{\lambda}{2NA} .$$

This means that the camera's resolution becomes proportionally better as we reduce the wavelength of the working light and increase the acceptance angle.

However, the camera's depth of field is reduced as the wavelength of the light becomes smaller, and depth of field is inversely proportional to the square of the acceptance angle. This relationship is given by:

$$\text{DOF} = \frac{\lambda}{(\text{NA})^2} .$$

Thus, there is a tradeoff between resolution and depth of field when we choose the working wavelength and acceptance angle. Figure 1 shows this tradeoff when applied to a camera system for which we want a resolution of at least  $0.1 \mu\text{m}$  with a depth of field greater than  $1 \mu\text{m}$ . In the figure, the upper line represents  $R = 0.1 \mu\text{m}$ , and all points *on or below* this line satisfy the resolution requirement. The lower line is  $\text{DOF} = 1 \mu\text{m}$ , and all points *on or above* this line satisfy the depth-of-field requirement. Hence, the intersection of the two areas is the operating region that achieves both requirements.

The camera's speed depends directly on the size of the aperture. (By *speed*, we mean how fast the camera can expose the recording medium using a given light source.) Therefore, a good camera design will have as large an NA as possible, consistent with the requirements for resolution and DOF just discussed.

Suppose we want to have the largest NA possible in our camera, while maintaining a resolution of at least  $0.1 \mu\text{m}$ . Then, Figure 1 shows that we must use a

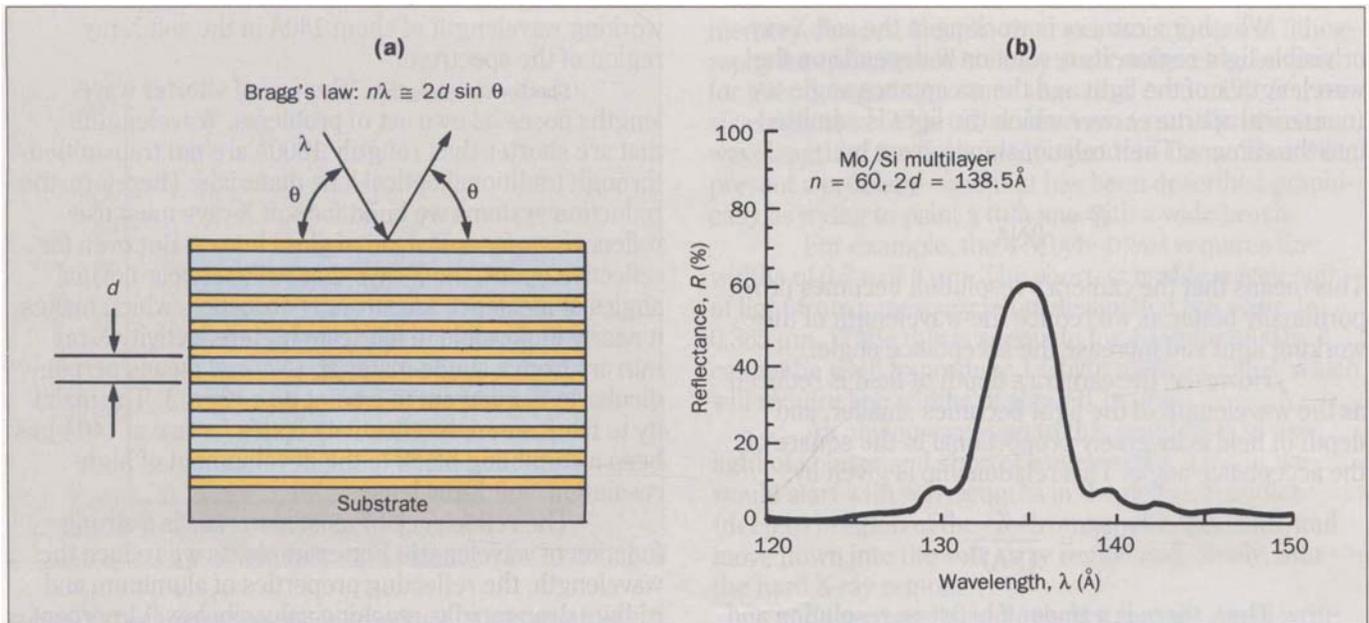
working wavelength of about  $140\text{\AA}$  in the soft X-ray region of the spectrum.

**Shorter wavelengths.** The use of shorter wavelengths poses its own set of problems. Wavelengths that are shorter than roughly  $1800\text{\AA}$  are not transmitted through traditional optical-lens materials. Therefore, the reduction systems we build for soft X-rays must use reflective surfaces instead of glass lenses. But even for reflective optics, the X-rays that strike at near-normal angles of incidence are strongly absorbed, which makes it nearly impossible to fabricate high-reflectivity X-ray mirrors from a single material. (*Normal* means perpendicular to the tangent to a point on a curve.) The inability to fabricate high-reflectivity optics for use at  $140\text{\AA}$  has been a stumbling block to the development of high-resolution, soft X-ray lenses.

The reflectance of most materials is a strong function of wavelength. For example, as we reduce the wavelength, the reflecting properties of aluminum and iridium drop rapidly, reaching values below 0.1 percent near our target wavelength of  $140\text{\AA}$ . Even the advanced coatings recently fabricated at Bell Laboratories, such as silicon carbide applied by chemical-vapor-deposition techniques, do not improve reflectivity at  $140\text{\AA}$ .

**Layered synthetic materials.** A solution to the reflectivity problem is the recent development of layered synthetic materials (LSMs). The LSMs are interference coatings that are fabricated on top of smooth substrates and dramatically improve reflectivity in the soft X-ray region. Until the multilayer coating technology became available, the fabrication of soft X-ray projection optics simply was not feasible.

Figure 2 shows how such interference coatings work. A thin-film sputtering system deposits alternating layers of materials onto the substrate. (See Figure 2a.) Because these materials have different indices of refraction for  $140\text{\AA}$  radiation, a small portion of the radiation is reflected at each interface. At a particular angle of incidence, called the Bragg angle, all these small reflections



**Figure 2. Properties of a layered synthetic material (LSM).** (a) Alternating layers of materials deposited on a substrate have different indices of refraction for 140Å radiation. At a particular angle of incidence, called the Bragg angle, the small reflections of radiation at each interface add coherently to produce an overall high reflectivity. The high reflectivity depends on the angle  $\theta$  of the light on the substrate and its wavelength  $\lambda$ . (b) Reflectance near 130Å for one of our coated substrates.

add up coherently to produce a high overall reflectivity. This high reflectivity depends on the wavelength of the light and the angle at which the light strikes the surface of the substrate.

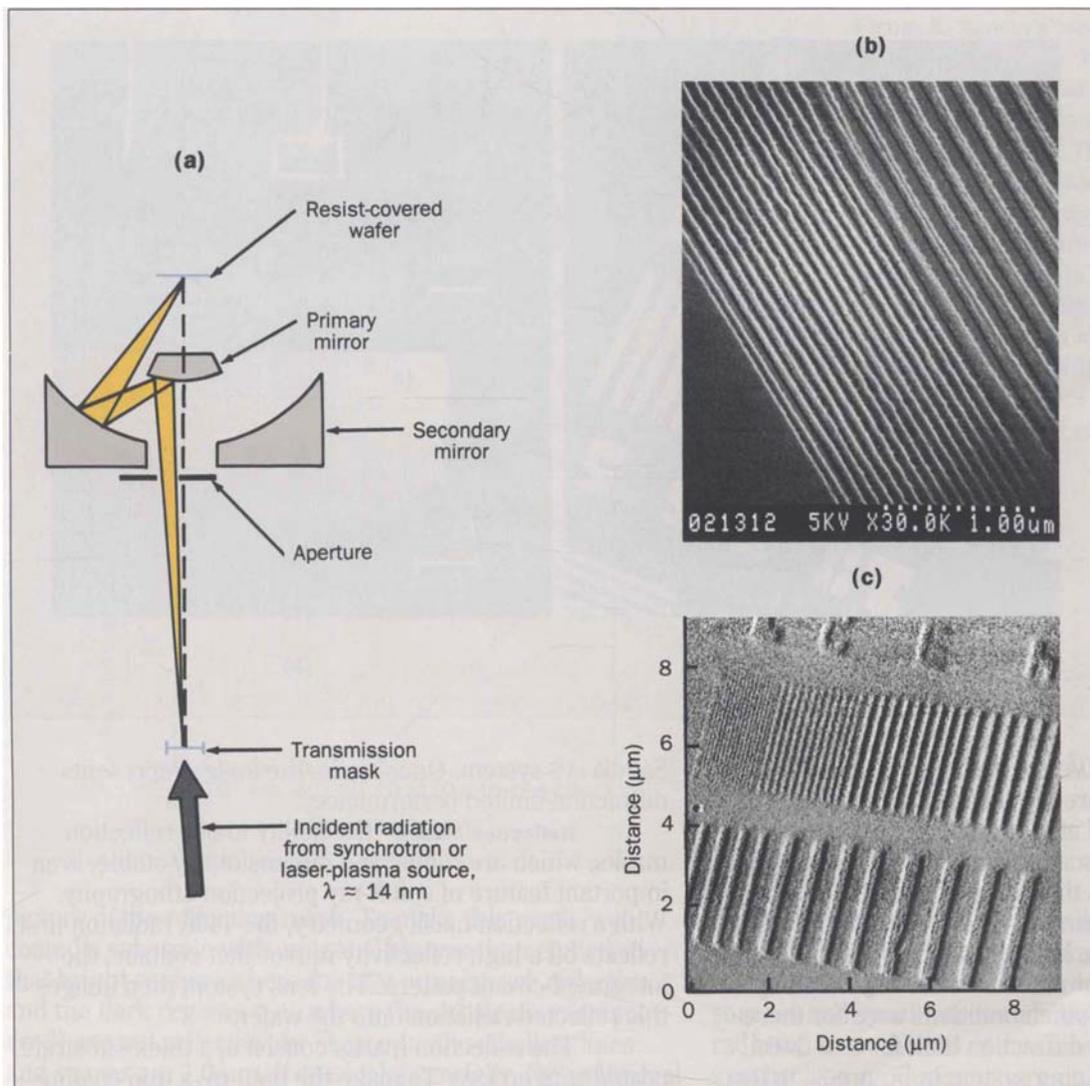
Figure 2b shows the reflectance of light near 130Å for one of our coated substrates. Notice that, within a band of about 10Å, the reflectivity is greater than 40 percent at normal incidence, a vast improvement over the otherwise normal reflectivity of less than 0.1 percent

at this wavelength. This high reflectivity is a result of the exceptional degree of control imposed on the thickness and surface smoothness of each of the layers that make up the total LSM.

Thus, one can achieve good throughput at the expense of having to design a camera system that uses light over the 10Å bandwidth. With the development of these specialized coatings (i.e., the LSMs) for substrates, projection imaging using soft X-rays has become possible.

### Imaging Results

To demonstrate the feasibility of soft X-ray projection lithography, AT&T Bell Laboratories set out to do reduction printing using radiation from a synchrotron at the National Synchrotron Light Source located at Brookhaven National Laboratories in Upton, New York.<sup>4</sup> The intent was to determine if an optical system could be fabricated and assembled that would image at or near the diffraction limit using 140Å radiation.



**Figure 3. Early tests used the Schwarzschild camera to print the image from a mask onto a wafer. (a) This two-mirror system has a reduction ratio of 20:1 for imaging with soft X-rays from a synchrotron or laser-plasma source (LPS). The images represent diffraction-limited performance. (b) The first tests used a transmission-test mask whose smallest lines and spaces were separated by  $1 \mu\text{m}$ . The smallest mask features projected onto the wafer at 20:1 reduction are separated by  $0.05 \mu\text{m}$ . (c) Atomic-force microscope image of the results obtained using the Sandia LPS system.**

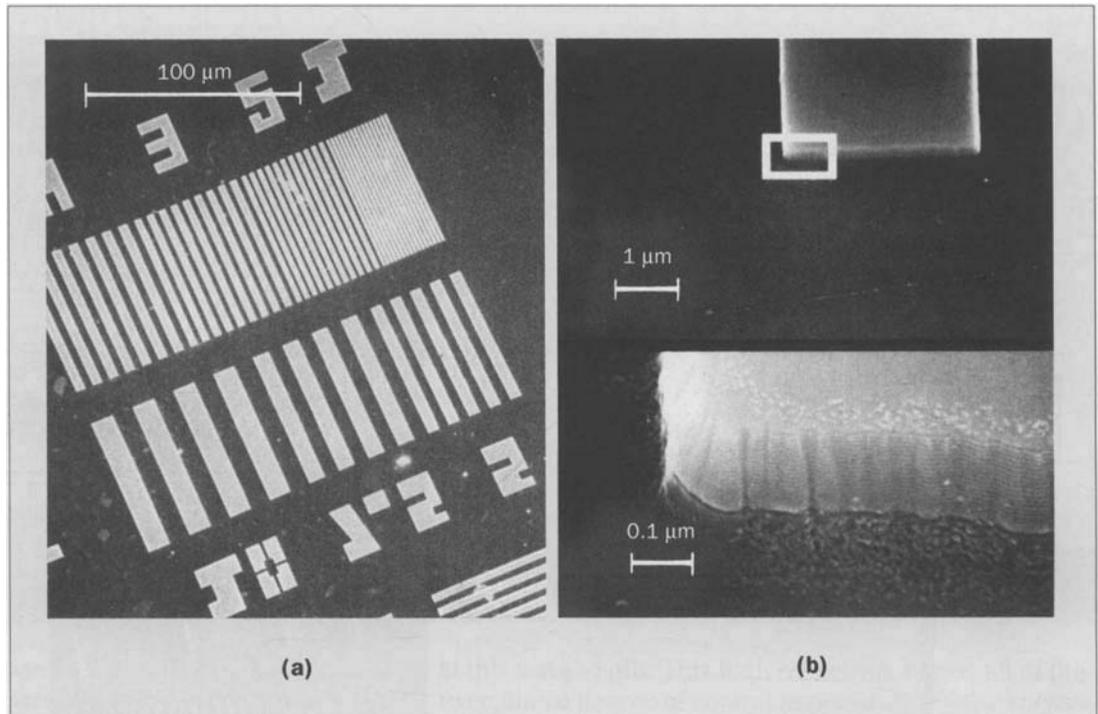
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The first tests of a soft X-ray projection system used a particularly simple lens design, called a *Schwarzschild* objective. This two-mirror system (illustrated in Figure 3a) was designed with a reduction ratio of 20:1;

that is, the image from a mask is reduced in size by a factor of 20 as it is printed onto a wafer.

We used a transmission-test mask composed of germanium lines and spaces written onto a  $7000\text{\AA}$ -thick

**Figure 4. A reflecting mask made by coating a substrate with an LSM and then etching away the LSM in some areas. (a) Bright regions where the LSM remains are reflective, and the dark regions (the substrate) are not. The smallest lines and spaces are 1.0  $\mu\text{m}$ . (b) This enlargement of a reflecting line shows the individual layers of molybdenum and silicon deposited to make the LSM.**



silicon membrane. At  $140\text{\AA}$ , the germanium *lines* on the mask are opaque, compared to the silicon membrane. The mask was fabricated at AT&T Bell Laboratories using a high-resolution, scanning-electron microscope.

Figure 3b shows the image projected onto the wafer. The smallest features on the mask were lines and spaces separated by  $1\ \mu\text{m}$ . In the photograph, the smallest mask features imaged onto the wafer are separated by  $0.05\ \mu\text{m}$ . Under the exposure conditions used for these tests, this represents the diffraction limit for  $\lambda = 140\text{\AA}$ .

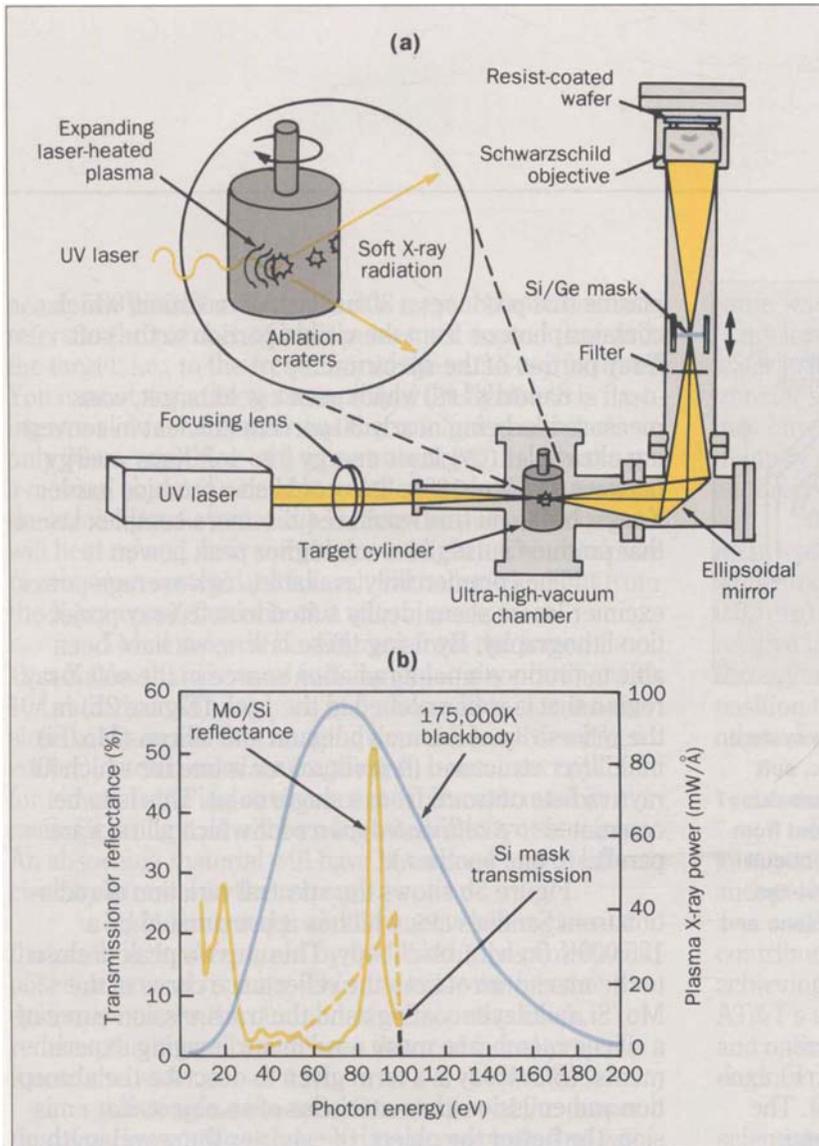
We used the imaging system in Figure 3a to test the feasibility of the LPS for soft X-ray projection lithography.<sup>5</sup> With the exception of the source and a collection mirror, the system is identical to the one used for imaging with synchrotron radiation. Figure 3c shows an atomic-force microscope image of the results obtained with the

Sandia LPS system. Once again, the image represents diffraction-limited performance.

**Reflection Masks.** The ability to use reflection masks, which are robust and dimensionally stable, is an important feature of soft X-ray projection lithography. With a reflection-mask geometry, the  $140\text{\AA}$  radiation first reflects off a high-reflectivity mirror that contains the integrated-circuit pattern. The lens system then images this reflected radiation onto the wafer.

The reflection masks consist of a thick substrate coated with an LSM. To make the pattern, a thin coating of metal or organic material can be applied on top of the LSM to spoil the reflectivity in desired regions. Alternatively, one can etch away the high-reflectivity LSM surface over areas where no reflection is wanted.

Figure 4 shows a scanning-electron microscope

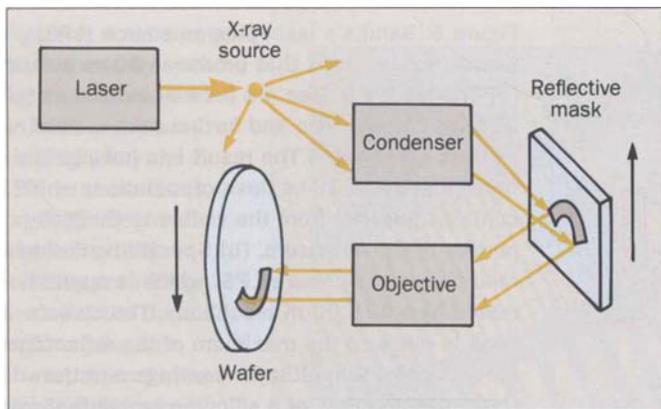


**Figure 5. Sandia's laser-plasma source (LPS) uses a KrF UV laser that produces 30-ns pulses. (a) The laser's pulses are focused onto a metallic target to vaporize and further heat a small amount of material. The result is a hot plasma that produces a 30-ns flash of radiation, which contains photons from the visible to the X-ray portion of the spectrum. (b) Spectral variation of radiation from Sandia's LPS, which is approximated by a 175,000K blackbody. The curve's peak is close to the maximum of the reflectance curve for Mo/Si multilayer coatings and the transmission curve of a silicon membrane mask used in the imaging experiments.**

picture of the reflecting mask. To make this mask, we coated a substrate with an LSM. This was then etched so that bright regions where the LSM remains are reflective and the dark regions (i.e., where the substrate was uncovered) are not reflective. In Figure 4a, the smallest lines and spaces are 1.0  $\mu\text{m}$ . If one looks carefully, the individual layers of molybdenum (Mo) and silicon (Si) that were deposited to make the LSM are visible in Figure 4b.

**Laser-Plasma Source.** From a manufacturing viewpoint, a key issue is the availability of bright, soft X-ray sources. As we mentioned earlier, the laser-plasma source

represents a potentially competitive alternative to synchrotron-radiation sources for X-ray projection lithography. One significant difference between laser-plasma sources and synchrotron-radiation sources is that the radiation from the LPS comes from a point, whereas a synchrotron produces a more or less collimated beam of radiation. If an imaging system uses an LPS, then the system must incorporate a condenser mirror to collect that portion of the soft X-rays that are radiated into a  $2\pi$  solid angle in front of the target. The collection mirror also illuminates the mask and directs this radiation into the



**Figure 6. Proposed soft X-ray projection lithography system.** The driver is a laser. A condenser collects light (i.e., soft X-rays) from the X-ray source and directs it onto a mask. The objective (a camera) captures the light scattered from the uncovered regions of the mask and images the circuit design from the mask. The camera is stationary, but the wafer and mask move across the camera's image plane and acceptance aperture, respectively.

entrance pupil of the imaging lens.

Figure 5a is a schematic of the Sandia laser-plasma source, which uses a krypton fluoride (KrF) excimer laser with an average power of 150W (watts). The excimer laser's output is a pulse that is 30 ns (nanoseconds) long at  $\lambda = 248$  nm (nanometers) and nominally contains 1.5 joules of energy. These pulses can be produced at a maximum rate of 100 Hz (hertz).

The 30-ns long laser pulses are focused onto a metallic target. When the laser pulse strikes the target drum, a small amount of material is vaporized (ablated) from the surface, creating ablation craters a few hundred micrometers in diameter. The remainder of the 30-ns long pulse further heats the vaporized material, raising it to higher temperatures. As the material heats up, it forms a nonequilibrium plasma that then emits electromagnetic radiation. The result is an extremely hot

plasma that produces a 30-ns flash of radiation, which contains photons from the visible portion to the soft X-ray portion of the spectrum.

Sandia's LPS, which uses a gold target, was measured as being nearly 30-percent efficient in converting ultraviolet (UV) laser energy into soft X-ray energy between 40Å and 180Å. LPSS could also produce harder X-rays, but to do this would require more complex lasers that produce pulses of much higher peak power.

The commercially available, high-average-power excimer lasers seem ideally suited to soft X-ray projection lithography. By using these lasers, we have been able to produce a point-radiation source in the soft X-ray region that is well matched to the peak (Figure 2b) in the reflectivity of the molybdenum and silicon (Mo/Si) multilayer structure. (A *point source* is one for which all rays radiate outward from a single point. This is to be contrasted to a *collimated source* for which all rays are parallel to one another.)

Figure 5b shows the spectral variation of radiation from Sandia's LPS, which is approximated by a 175,000K (kelvin) blackbody. This curve's peak is close to the maximum of both the reflectance curve of the Mo/Si multilayer coatings and the transmission curve of a silicon-membrane mask used in our imaging experiments. (*Blackbody* is a term given to describe the absorption and emission characteristics of an object. For emission, the hotter the object, the shorter the wavelength of the emitted electromagnetic radiation. For example, the sun is characterized by a 6000K emission spectrum that peaks in the visible region, near 4800Å. The Sandia LPS produces a plasma that has a characteristic temperature of about 175,000K, which peaks near 160Å.)

**Manufacturing Tool Design.** Based on our results, we have begun to design a prototype exposure system that uses reflective optics and a compact, laser-plasma source. Figure 6 shows this soft X-ray projection lithography system.

The light from a laser (i.e., the driver), which must have a high-repetition rate and an average power of

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nearly 500W, will strike a suitable target. (*Repetition rate* refers to the number of laser pulses per second that strike the target; i.e., to the frequency of the soft X-ray flashbulb. You cannot scan the wafer rapidly if the lightbulb is flashing at a slow rate. Recall that the soft X-ray pulse lasts only 30 ns, and think of it as a strobe light that illuminates a moving object. To be able to follow the object's motion, the strobe has to be rapid.) During the pulse, the target will heat up and emit soft X-rays (or light). The *condenser* (a mirror or system of mirrors) will collect the light from the X-ray source and direct it onto a mask.

This mask will be different from the transmission masks that are used in X-ray proximity printing with 10Å radiation. Although we had also used thin transmission masks in our first imaging experiments (described earlier), such masks are fragile and, hence, not optimum for a manufacturing environment. The mask used in a manufacturing tool will be a high-reflectivity LSM mirror. An absorbing material will have been used to write the circuit pattern onto the mirror.

Light scattered from the uncovered regions of the mask is then captured by the *objective*, a camera composed of several mirrors. This camera—the heart of the system—images the circuit design from the mask, reduces the image by at least a factor of 5, and projects it onto the wafer.

**Additional requirements.** Our studies of the properties of various designs have led us to conclude that we will need a scanning system. That is, to expose large-area wafers, the camera must scan across the mask and the wafer. In practice, the camera is stationary, while the wafer is moved across the camera's image plane and the mask is moved across the camera's acceptance aperture. Because the camera reduces the image of the mask onto the wafer, the scanning requirement introduces another complication. That is, for a reduction factor of 5, the wafer must be scanned at one-fifth the rate at which the mask is scanned.

In addition, a practical lithographic system must be able to align or position multiple images onto the

same wafer. When semiconductor circuits are built, many levels have to be fabricated on each chip, and the wafer is processed after each lithographic or pattern-transfer step. For example, as many as 20 different levels may have to be imaged and then processed on a single memory chip, all precisely aligned with respect to one another. The alignment system provides this positioning.

In soft X-ray projection lithography, the alignment system must scan the mask relative to the wafer while maintaining precise positioning (i.e., better than 0.02 μm). Interferometers will control the wafer's motion relative to the mask. An optical aligner, which works through the camera that images the X-rays, will precisely position the image from one mask onto the images from other masks.

#### **Technology Transfer—Lessons Learned**

The rapid progress demonstrated so far by this joint venture is the result of several important technical and, perhaps, cultural factors.

AT&T Bell Laboratories and Sandia have each contributed unique capabilities that were essential to achieving a well-defined set of technical objectives. AT&T's strengths lie in the areas of multilayer growth and optics design. Sandia's are laser-plasma sources and engineering design.

We were able to assemble a team of top-calibre scientists who were strongly committed to a common, overriding goal—U. S. competitiveness in a key national technology: microelectronics. A compelling, shared motivation enhances the way any research team works together toward a common goal.

Perhaps most important, the culture of technology transfer involves the continuous sharing of knowledge by people working together in a partnership. It is not simply the transfer of a set of drawings or a piece of equipment. For technology transfer to succeed, the partners must establish an atmosphere of trust and cooperation, so that knowledge flows smoothly and ideas are openly shared.

### Summary

As we move rapidly toward the turn of the century, new lithographic technologies must be developed to reach the design goals for integrated circuits, such as 1-Gbyte memory devices and beyond. As we have shown here, soft X-ray projection lithography is one alternative that is capable of printing the feature sizes required to reach this goal.

The Sandia and AT&T Bell Laboratories team has developed a soft X-ray projection lithography system. This system uses a laser-plasma source for soft X-rays and reflective optics with unusual LSM coatings.

The path ahead is extremely challenging. It requires advances in optics design and fabrication; large-area, multilayer coatings; high-average-power laser systems; and demanding wafer-alignment tolerances. All must be packaged into a compact, reliable, and easy-to-use exposure tool if SXPL is to be accepted and used by semiconductor manufacturers.

While the challenges are great, the investment in this technology is well founded. If successful, this technology can have a significant impact on semiconductor manufacturing in the future.

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