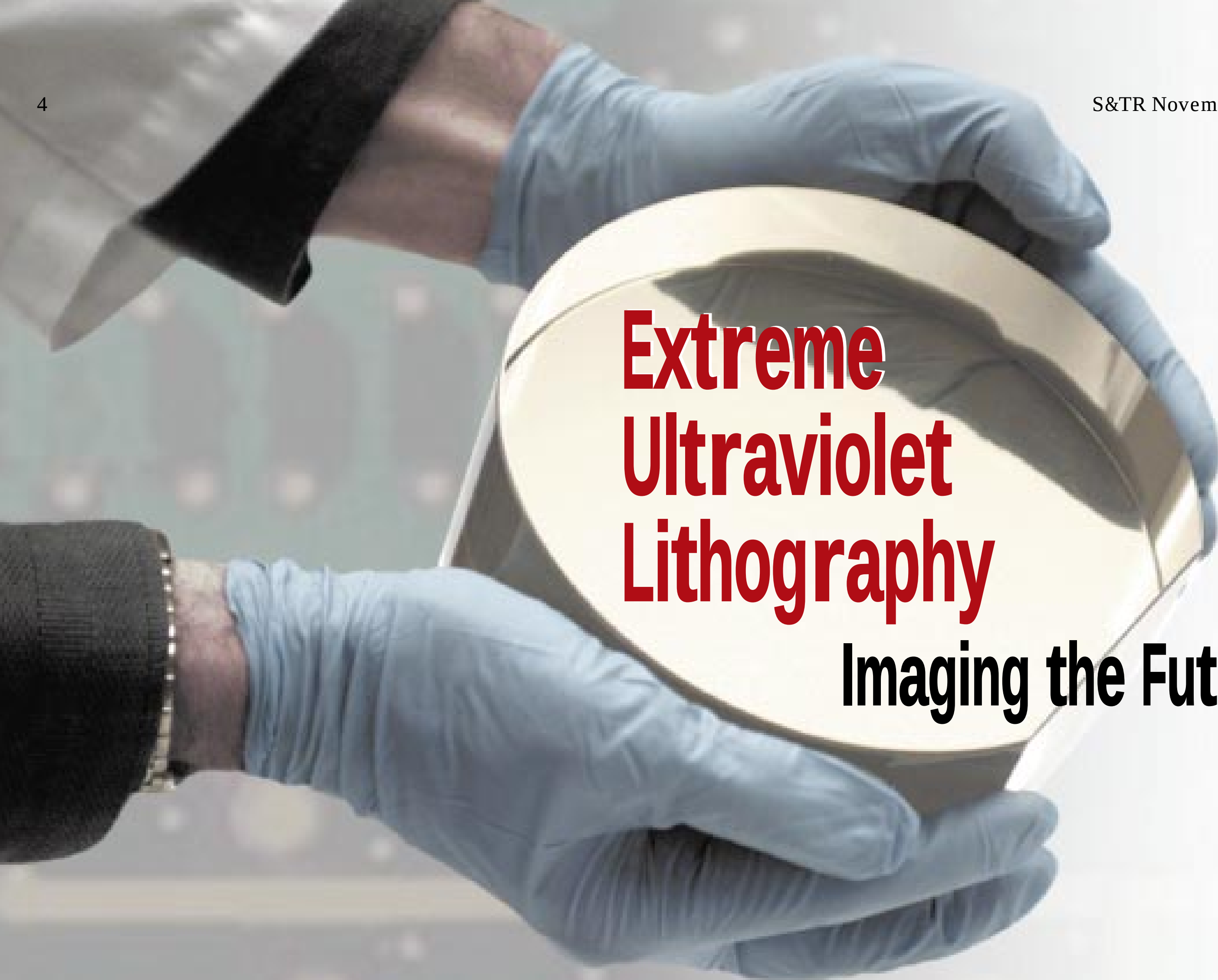


Extreme Ultraviolet Lithography

Imaging the Future

Livermore researchers are part of a collaboration between private industry and DOE laboratories dedicated to making extreme ultraviolet lithography the technology of choice for manufacturing the next generation of microcomputer chips.

TWENTY-FIVE years ago, the computing equivalent of today's laptop was a room full of computer hardware and a cartload of punch cards.

Since then, computers have become much more compact and increasingly powerful largely because of lithography, a basically photographic process that allows more and more features to be crammed onto a computer chip. Light is directed onto a mask—a sort of stencil of an integrated circuit pattern—and the image of that pattern is then projected onto a semiconductor wafer covered with light-sensitive photoresist. Creating circuits with smaller and smaller features has required using shorter and shorter wavelengths of light.

However, current lithography techniques have been pushed just about as far as they can go. They use light in the deep ultraviolet range—at about 248-nanometer wavelengths—to print 150- to 120-nanometer-size features on a chip. (A nanometer is a billionth of a meter.) In the next half dozen years, manufacturers plan to make chips with features measuring from 100 to 70 nanometers, using deep ultraviolet light of 193- and 157-nanometer wavelengths. Beyond that point, smaller features require wavelengths in the extreme ultraviolet (EUV) range. Light at these wavelengths is absorbed instead of transmitted by conventional lenses. The result: no light, no image, no circuit.

Semiconductor manufacturers are, therefore, at a critical juncture. Soon, they must decide which lithographic horse to back in the race to the next generation of microchip manufacturing. There are currently four possible alternatives: EUV, x-ray, electron-beam, and ion-beam lithography.

Creating a Virtual Laboratory

Two years ago, three Department of Energy national laboratories—Lawrence Livermore, Lawrence Berkeley, and Sandia/California—formed the Virtual National Laboratory (VNL) to research and develop extreme ultraviolet lithography (EUVL) technology. The VNL is funded by the Extreme Ultraviolet Limited Liability Company—a consortium of Intel Corporation, Motorola Corporation, Advanced Micro Devices Corporation, and Micron Technology, Incorporated—in one of the largest cooperative research and development agreements within the Department of Energy. The three-year, $250-million venture is dedicated to developing the EUVL technology for commercial manufacturing of computer chips and to move this technology into production facilities in the first decade of the 21st century.

Each national laboratory brings unique contributions to this effort. Lawrence Livermore supplies its expertise in optics, precision engineering, and multilayer coatings. Sandia provides systems engineering, the photoactive polymer thin film exposed by the light, and the light source. Berkeley contributes its Advanced Light Source capability to generate EUV light to characterize optics and resists at the nanometer scale.

The VNL's lithography system uses mirrors to project the image of a reflective mask onto the photoresist-coated semiconductor wafer. Ultimately, this system will enable a microchip to be manufactured with etched circuit lines smaller than 100 nanometers in width, extendable to below 30 nanometers. The resulting microprocessors would be a hundred times more powerful than those made today. Memory chips would be able to store a thousand times more information than at present.

"Lithography is generally viewed as the enabling technology for each new generation of semiconductor devices," says Don Sweeney, Lawrence Livermore's program manager for EUVL. "To put this technology into production facilities in 10 years, we need to show that the technology can work under real manufacturing conditions."

The VNL's current focus is on building and integrating the necessary

What's at Stake

> . . . [T]he first 30 years of the integrated circuit had from two to five times the impact on the U.S. economy as the first 30 years of the railroad. Or, to put it another way, the transformation of the nineteenth century U.S. economy by the railroad took 60 years to achieve half the effect that microelectronics had over 30 years.
>
> —Kenneth Flamm
> "More for Less: The Economic Impact of Semiconductors"
> December 1997

Semiconductors are ubiquitous in our lives. They are found in our cars, televisions, radios, telephones, stereos, personal computers, children's toys—even dishwashers and ovens. According to research conducted by the Semiconductor Industry Association and the World Bank, each person worldwide uses on the average about ten million transistors in a lifetime, with this consumption increasing 55 percent each year. By the year 2008, projections are that each person will consume a billion transistors.

It's no wonder then that the annual sale of semiconductors worldwide will soon reach about one trillion dollars—the equivalent of the gross national product of the United States. Furthermore, it's no wonder that the next generation of lithographic technology—which is seen as the "gating technology" to the next generation of integrated circuits—is of such great interest to semiconductor manufacturers throughout the world.

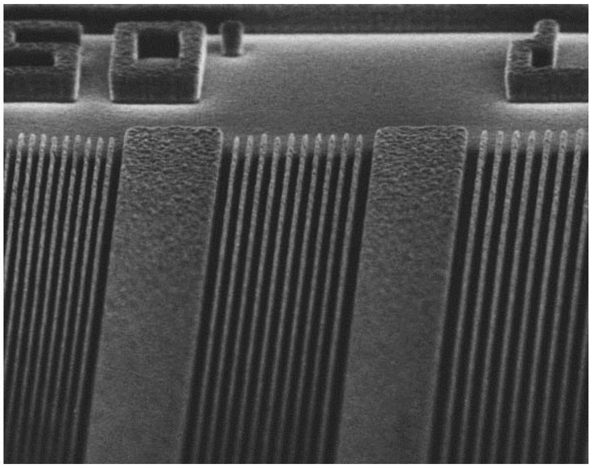
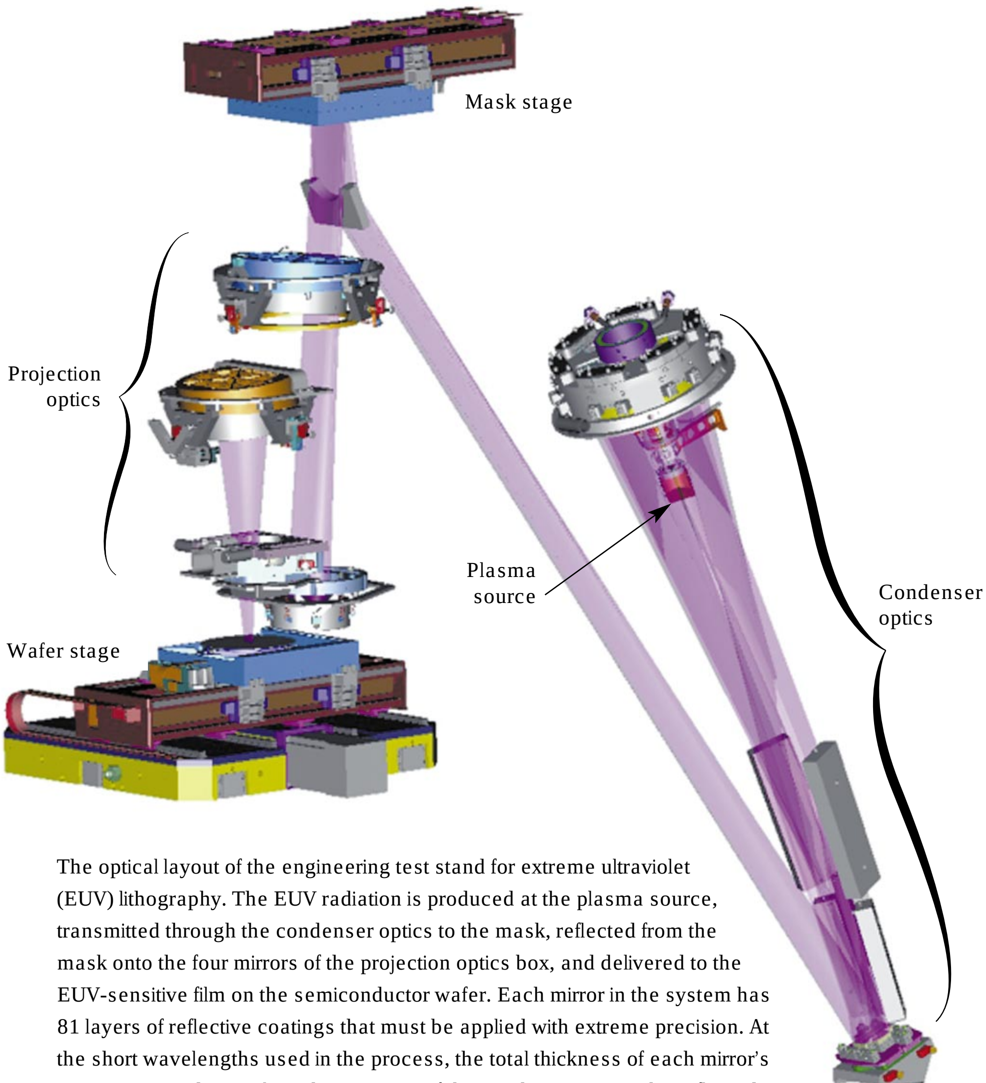


Photo courtesy of Sandia National Laboratories/California.

Using a prototype system, the Virtual National Laboratory has successfully printed lines as small as 50 nanometers (billionths of a meter) wide in photoresist. Current lithographic tools used in the semiconductor industry print patterns with 180-nanometer-size features.



The optical layout of the engineering test stand for extreme ultraviolet (EUV) lithography. The EUV radiation is produced at the plasma source, transmitted through the condenser optics to the mask, reflected from the mask onto the four mirrors of the projection optics box, and delivered to the EUV-sensitive film on the semiconductor wafer. Each mirror in the system has 81 layers of reflective coatings that must be applied with extreme precision. At the short wavelengths used in the process, the total thickness of each mirror's coatings must deviate less than an atom if the mask pattern is to be reflected without distortion. One such mirror is shown on p. 4.

technologies into an engineering test stand (ETS). Each national laboratory spearheads specific development areas for the ETS and for the systems beyond. Lawrence Livermore is leading the efforts to develop the optical systems and components, thin films, masks, and submicrometer metrology required for EUVL.

Brighter Light Is Key

The ETS (see the box on p. 7) includes a condenser optics box and a projection optics box. Both boxes house complex optical trains of precision concave and convex aspherical mirrors.

The main role of the condenser optics box is to bring light to the reflective pattern on the mask. "We want to bring as much light to the mask and, ultimately, the wafer, as possible," explains Sweeney. "The more light we deliver, the shorter the exposure time. It's like taking a picture with a camera. A picture taken in bright noonday sun requires a shorter exposure time than does a picture of the same scene taken at twilight."

For the semiconductor industry, brighter EUV images mean shorter exposure times, which translate to manufacturing more chips at a faster rate. The optics design team from Lawrence Livermore and Sandia designed a condenser optics system that collects and transports a significant fraction of the EUV light from the source to the reflective mask.

Once the image is reflected from the mask, it travels through the projection optics system. According to Sweeney, the projection optics box is the optical heart of the lithographic exposure system. "It is to the system what an engine is to a car," he explains. The four mirrors of the ETS projection optics system reduce the image and form it onto the wafer. "Again, imagine using a pocket camera. The camera lens transmits an image to the film, which—like the wafer—has a light-sensitive surface," says Sweeney.

The optics teams are now working on advanced designs for the projection optics. They have a six-mirror design that promises to extend EUVL systems so that they can print features as small as 30 nanometers— a significant jump from the 70-nanometer limit of the ETS.

According to Sweeney, extendability to smaller features is an important requirement for whatever lithographic technology the semiconductor industry finally decides to back.

Applying Uniform Thin Films

Part of the success of the EUVL technology is due to the immense strides Lawrence Livermore has made in producing the highly reflective multilayers that are used on the ETS's optical mirrors as well as on the mask.

The projection and condenser optical systems require mirrors that reflect as much EUV light as possible. Manufacturing these mirrors has been a challenge because, in addition to being highly reflective, they must have surface coatings that are essentially perfectly uniform.

Lawrence Livermore and Lawrence Berkeley developed advanced multilayer coatings of molybdenum and silicon that can reflect nearly 70 percent of the EUV light at a wavelength of 13.4 nanometers. Applying these coatings evenly is a difficult task even when a mirror is flat, but EUVL mirrors are either convex or concave. Any small nonuniformity in the coatings destroys the shape of the optics and results in distorted patterns printed on the chips.

In the past year, the development of a new precision deposition system provided a major advance in applying these thin films to optics. (See *S&TR*, October 1999, p. 12.) This system, which won a 1999 R&D 100 Award, is so precise that 81 layers of molybdenum and silicon, each about 3.5 nanometers thick, can be deposited over a 150-millimeter area so that the total thickness over the surface deviates by less than an atom. The technique can be used to coat mirrors as large as 40 centimeters in diameter.

The Mask-Making Challenge

Industry experts generally agree that the biggest challenges and risks for the next generation of lithography systems involve the mask—that is, the master pattern used to "print" the semiconductor circuits onto the silicon wafers or chips. The technology that successfully overcomes the hurdles of mask production has a good chance of becoming the preferred choice.

In EUVL, a mask is produced by applying multilayers of molybdenum and silicon to a flat substrate. The circuit pattern is produced by applying a final

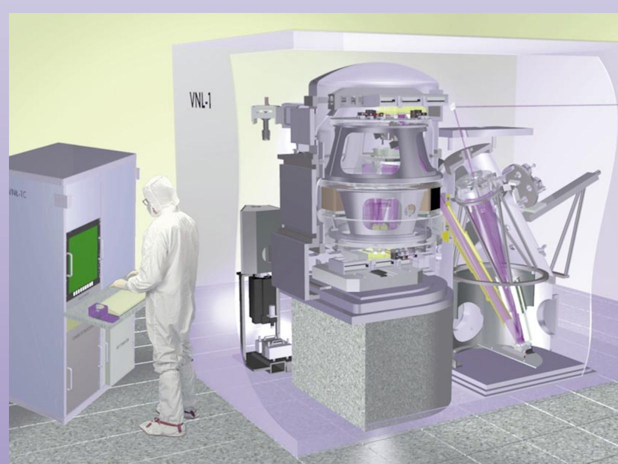
The extreme ultraviolet lithography projection optics system in final assembly.

The Engineering Test Stand Provides a Prototype

The Virtual National Laboratory is developing, designing, and building a prototype extreme ultraviolet lithography (EUVL) system called the engineering test stand (ETS) at Sandia National Laboratories/California. The ETS uses laser-produced plasmas to supply the extreme ultraviolet radiation needed. The radiation travels through a complex condenser optics system before reflecting from a lithographic mask. That image is then projected by the projection optics onto a semiconductor wafer.

"The basic building blocks are the same as those found in systems operating at visible wavelengths, except their forms are different, because of the short wavelength of EUV," says Don Sweeney, Lawrence Livermore's program leader for EUVL.

Because all materials, including nitrogen and oxygen, absorb EUV, the machine must operate in a vacuum and use reflective mirrors and masks. The ETS has six essential subsystems: a laser-produced plasma EUV source, condenser optics, projection optics, a mask, precision scanning stages, and a vacuum enclosure.



A conceptual drawing of the extreme ultraviolet engineering test stand. The goal of the ETS is to demonstrate how ultraviolet wavelengths can be used to print patterns on integrated circuits at production levels and sizes.

EUV-absorbing metal layer and then etching away the metal to form the image of the circuit.

One key requirement is to produce a mask with essentially no defects. Any small defect ends up being replicated, or printed, in the lithography process onto the computer chips being manufactured, thus damaging the chips' complex circuitry. A key breakthrough in this area was the development of an Ultra Clean Ion Beam Sputter Deposition System about two years ago. This system—also an R&D 100 Award winner—produces precise, uniform, highly reflective masks with fewer defects than those produced by conventional physical deposition processes. (See *S&TR*, October 1997, p. 8.) In April 1999, the team made significant improvements to the system's sputtering shield design and other operational parameters. The system now consistently produces fewer than 0.1 defects per square centimeter—a factor-of-8 improvement over defect densities produced in 1998.

In fact, under the best operating conditions, the system adds as few as 0.04 median defects per square centimeter during a coating run of 25 wafers. The ultimate goal for the system is to add no more than 0.001 defects per square centimeter to the finished wafer blank.

The system has also been upgraded to process 200-millimeter wafers—the size used in industry—up from 150-millimeter wafers. The ability to process larger wafers for mask substrates means both that the technology is working with industry standards and that patterns for larger chips can be placed on the wafer.

The Lawrence Livermore team has also conducted groundbreaking experiments looking at the propagation of defects during multilayer film growth. All masks have defects of some kind—some more, some less. First of all, there are defects that arrive on the wafer from the manufacturer. These are analogous to the pinholes and dust one finds on photographic negatives. Defects smaller than a certain critical size are covered up by the film layers and present no problem. However, defects larger than this critical size persist through the coating process and must be repaired or reckoned with in some way.

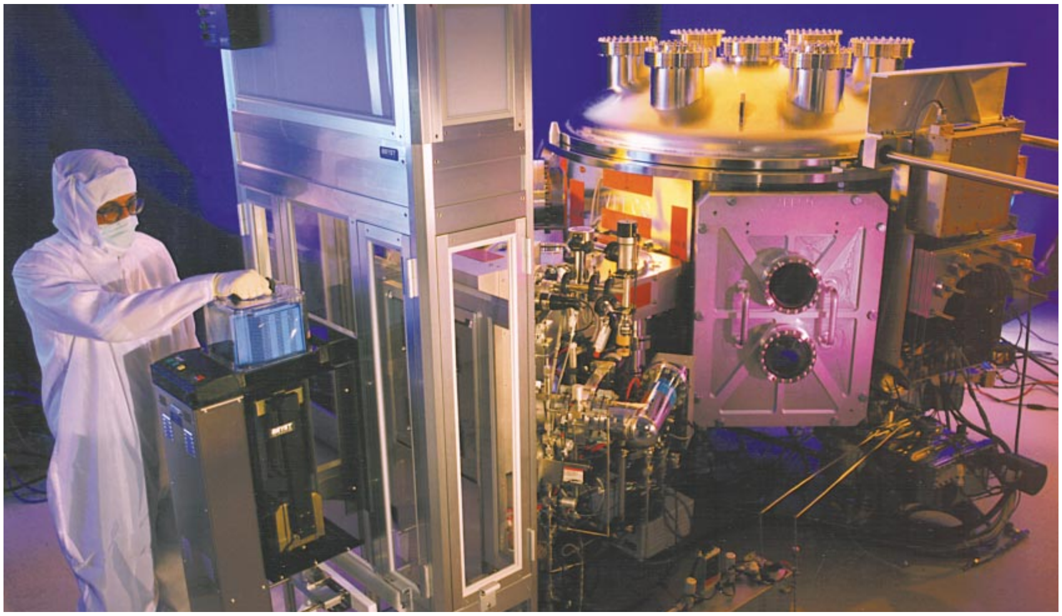
There are also defects created by the coating process itself: a few atoms too many in any one area can create a bump that will affect the final circuit pattern. The question becomes, what is this critical size? "We've been modeling for a long time to see how different sizes and kinds of defects affect the final product," says Scott Burkhart, group leader for mask blank development. "We finally conducted experiments that are setting the lower bound of critical defect size."

The group has also made strides in repair strategies for mask defects. "One mask can cost tens of thousands of dollars," notes Burkhart. "When possible, repairing the defects saves the industry a lot of money."

Measuring at the Atomic Level

Until recently, it was impossible to accurately measure a mirror surface for high and low spots of a few atoms. An R&D 100 Award–winning interferometer developed at the Laboratory two years ago—called the phase-shifting diffraction interferometer (PSDI)—changed all that. (See *S&TR*, October 1997, p. 6.)

Like all interferometers, the PSDI uses the interference pattern of two waves of light to measure objects or phenomena. These light waves are usually imperfect because of the

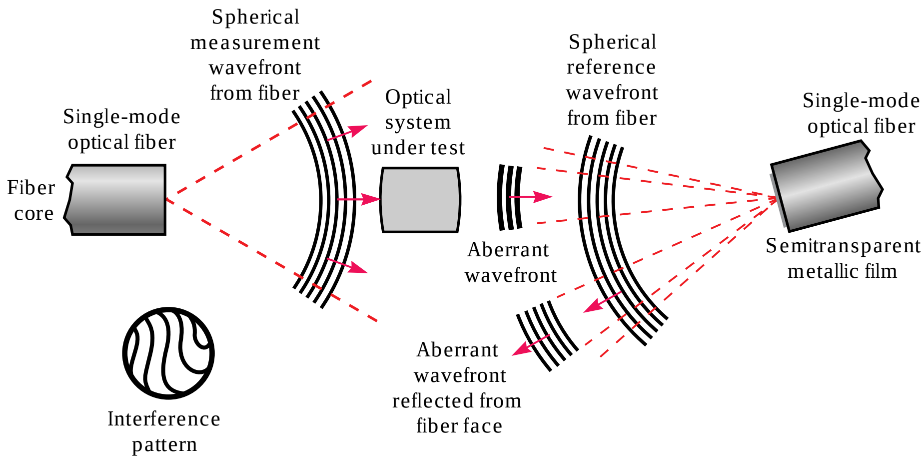


The Ultra Clean Ion Beam Sputter Deposition System, developed at Lawrence Livermore, is used to produce precise, uniform, highly reflective masks. A key requirement of the next-generation lithography system is that it produce virtually defect-free masks. The system contributes fewer than 0.1 defects per square centimeter to each mask. The ultimate goal for extreme ultraviolet lithography is to add no more than 0.001 defects per square centimeter to a finished wafer blank.

imperfect condition of the surface or lens from which they emanate. Any imperfection introduces error into the measurements. The PSDI produces a nearly perfect spherical wavefront using diffraction. In diffraction, light passes around an object or through a hole, breaking up in the process. In the PSDI, two light beams pass through two separate optical fibers. When light exits the surface of each fiber, it diffracts, forming nearly perfect spherical wavefronts. Because the two wavefronts are generated independently, their relative amplitude and phase can be controlled, providing contrast adjustment and phase-shifting capability for the highest possible accuracy.

The measurement wavefront passes through the optical system being tested, which induces aberrations in the wavefront and causes it to focus on the endface of the other fiber. Here, the wavefront reflects off a semitransparent metallic film of the fiber end's surface and interferes with the reference wavefront to generate an interference pattern. The pattern is then recorded by a charge-coupled-device camera.

Over the past three years, many EUV optics have been measured using this interferometer, including both concave and convex spherical and aspherical mirrors and completed projection systems. The PSDI is now a reliable production tool for measuring the overall surface shape of those aspherical optics that have a specification of 0.50 nanometers or less and has successfully measured errors in the surface shape down to 0.35 nanometers. The Livermore metrology team is upgrading the system so that it can be used to measure errors in the overall surface shape as small as 0.15 nanometers.



Schematic of the phase-shifting diffraction interferometer which uses two single-mode optical fibers. In this example, the interferometer is testing a lens, but the setup is similar for testing mirrors.

EUV Pulling Ahead in the Race

Last December, the VNL's work paid off with a vote of confidence from International Sematech, a privately funded organization of semiconductor manufacturers.

At its annual meeting, International Sematech evaluated the four next-generation lithographic technologies—EUV, x-ray, electron-beam, and ion-beam—and strongly recommended EUV lithography. "Their recommendation gave our efforts important momentum," notes Sweeney. "It validated what we already knew: that we have a winning combination in the three national laboratories and our industrial partners and that our strength comes from working together."

—*Ann Parker*

Key Words: Extreme Ultraviolet Limited Liability Company, extreme ultraviolet lithography (EUVL), masks, phase-shifting diffraction interferometer (PSDI), precision deposition system, reflective multilayers, submicrometer metrology, thin films, Ultra Clean Ion Beam Sputter Deposition System, Virtual National Laboratory (VNL).

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About the Scientist

DONALD SWEENEY received his B.S., M.S., and Ph.D in mechanical engineering from the University of Michigan at Ann Arbor in 1968, 1969, and 1972, respectively. He was a professor at Purdue University from 1972 to 1983, after which he became a department manager at Sandia National Laboratories/California and assumed responsibility for a research program in optical diagnostics.

Sweeney joined Lawrence Livermore's Advanced Microtechnology Program (AMP) in early 1993 and soon became deputy program leader for Optics Technology. In February 1999, AMP reorganized and became the Information Science and Technology Program, where he is currently deputy program leader for Extreme Ultraviolet Lithography and Advanced Optics.