EUV Light Sources for Next-Gen Lithography

FAIZ RAHMAN

After a long period of development, sophisticated machines that generate streams of extreme-ultraviolet radiation from laser-produced plasmas are on the cusp of taking chip manufacturing to the next level.

Courtesy of ASML Lithography

Since its beginnings, commercial chip manufacturing has relied on photolithography, to pattern the incredibly small features of transistors and interconnects found on modern integrated circuits (ICs). And lithography has had to find ways to enable printing of ever-smaller features, with the ongoing demand for shrinking circuit geometries. Because of the limitations imposed by optical diffraction, as the feature sizes to be printed have shrunk, the wavelength of the light used for lithographic patterning has also needed to come down. Thus, the mercury i-line (365 nm) lithography of early years gradually gave way to 248-nm (KrF excimer laser) lithography, and then to the 193-nm (ArF excimer laser) radiation used in present-day production.

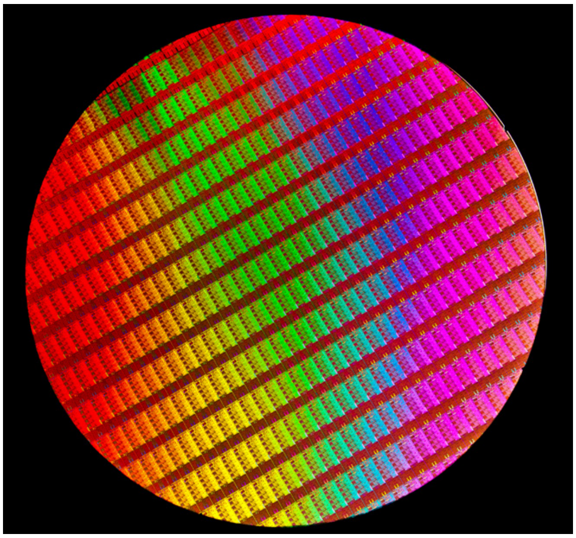
Yet even these deep-ultraviolet (DUV) wavelengths fall short of future needs, given continual pressure for downsizing of component dimensions on monolithic ICs. Indeed, the semiconductor industry has recognized for more than two decades the need ultimately to move to significantly shorter wavelengths—and the quest for new sources of very-short-wavelength UV radiation suitable for semiconductor lithography has been a long one.

This feature looks at the state of the art of such high-brightness sources of extreme-ultraviolet (EUV) radiation—particularly those that work by laser ablation of tin droplets, which has emerged as the most promising technique for generating EUV light at production scale for the semiconductor fab.

The difficult leap to EUV

Equipment for fabricating IC wafers is notoriously expensive. Building a state-of-the-art chip-making plant now costs several billion U.S. dollars, and process tools are so costly that fabs need to run continuously to earn an adequate return on investment. In that environment, new tools must undergo a costly, prolonged qualification period, to fine-tune the manufacturing process to obtain optimum chip yields. Not surprisingly, semiconductor fabs try, as far as possible, to stick to established manufacturing tools and processes.

As a result, the reigning DUV lithography technologies have repeatedly been extended through clever tricks—including optical proximity correction, double patterning and lens immersion—to avoid the need to introduce a brand-new, shorter-wavelength light source. Yet even with those tricks, it will prove increasingly difficult to print the most critical layers on tomorrow's memory and logic wafers. It's been clear for years that, as semiconductor technology nodes approach and surpass the 10-nm milestone, lithography will need to switch to a new, much shorter wavelength.



A 300-mm-diameter silicon wafer containing microprocessor dies. Similar wafers will be printed in the future using EUV lithography tools.

Courtesy of Intel Corporation

After examining several prospective technologies during the 1990s, the semiconductor industry gradually reached a consensus that photolithography at the extreme-ultraviolet (EUV) wavelengths around 15 nm offers the best way forward. In large part, that's because EUV technology retains many of the features that have long been familiar to wafer manufacturers, such as manipulation of electromagnetic radiation and the use of reticles and steppers. Yet the wavelengths of EUV radiation are so short that they mandate a dramatic shift in how lithography is implemented. The semiconductor industry has thus been very reluctant to migrate to EUV-based lithography—and are now moving in that direction only grudgingly, after all of the tricks and techniques in the current lithography toolbox have been exhausted.

Generating EUV radiation

While EUV lithography has been on the semiconductor industry's technology roadmap for much of the past decade, its introduction to the fab floor has repeatedly been pushed out further into the future. The biggest reason for that delayed transition is that both generating adequate amounts of this extremely short-wavelength

1047-6938/18/03/42/8-$15.00 ©OSA

It's been clear for years that, as semiconductor technology nodes approach and surpass the 10-nm milestone, lithography will need to switch to a new, much shorter wavelength.

radiation, and then using it to perform lithography, pose formidable challenges.

Electromagnetic radiation at wavelengths of a few tens of nanometers is hard to produce. Ordinary blackbody sources, based on a Boltzmann distribution of excited electron states in neutral atoms, cannot produce such energetic radiation; neither can run-of-the-mill electrical-discharge sources. This leaves only two options—synchrotron sources and specially prepared high-energy plasmas—as viable sources of EUV radiation.

A high cost of ownership, difficulty in operation and maintenance, and the rather low powers available in projected solid angle make synchrotron sources a relatively poor fit for commercial wafer production. Laser-generated thermal plasmas, usually known as laser-produced plasma (LPP), on the other hand, can generate EUV wavelengths at high power and with high enough conversion efficiencies to be seriously considered for lithography applications. And such sources, after long development, have now reached the threshold of maturity for use in the next generation of commercial optical lithography.

Cold electrical discharges in gases and gas mixtures generate visible and UV radiation through electronic transitions in mostly neutral atoms, but that radiation does not go beyond the DUV region given the relatively low separations of available energy levels in neutral atoms. To go to shorter wavelengths (that is, more energetic photons) requires creating singly and multiply ionized species with larger separations between energy levels. EUV photons can and have been produced through short-pulse, high-current electrical discharges in a suitable gas, such as xenon. But the technique is inefficient and very difficult to scale up to high flux levels, and thus hasn't been developed for applications requiring strong EUV emission.

For high flux levels, LPP sources are much more practical. In a laser-driven EUV source, laser energy, usually in the form of rapid, ultrashort pulses, is focused on a solid, liquid or gaseous target. Absorption of high laser peak powers results in the formation of a dense, hot plasma, much like those found in certain highly energetic stellar sources. Ionized atoms in such thermal plasmas radiate at many wavelengths, from deep in the infrared all the way to soft X-rays.

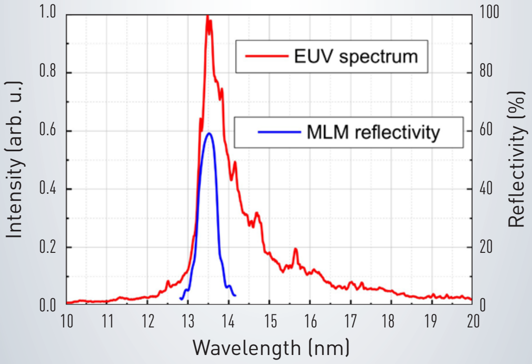
Doing it with lasers

The laser's potential to deliver concentrated radiant energy to chosen targets has been crystal-clear since its invention. Industrial applications based on heat treatment of materials, such as cutting, welding and

Why tin plasma?

Struck by pulses of intense infrared radiation from a CO_2 laser, tin ablates within nanoseconds, vaporizing almost instantaneously into an ionized tin plasma. The thus-formed plasma includes ions of several different charge states. Other metals also can form plasmas under laser irradiation; why is tin the choice for EUV generation for lithography applications in particular?

Tin derives its usefulness in lithography from its EUV spectrum. Specifically, its plasma emits strongly in the region not far from that of soft X-rays (wavelengths of 10 nm and below), with a prominent peak close to 13.5 nm—the wavelength sweet-spot for the next generation of semiconductor lithography.



Spectra of tin plasma emission generated on irradiation of tin droplets with CO_2 laser pulse (red line), and reflectance spectrum of the Mo/Si multilayer mirrors (MLMs) used for all optical manipulations in the source-scanner system (blue line).

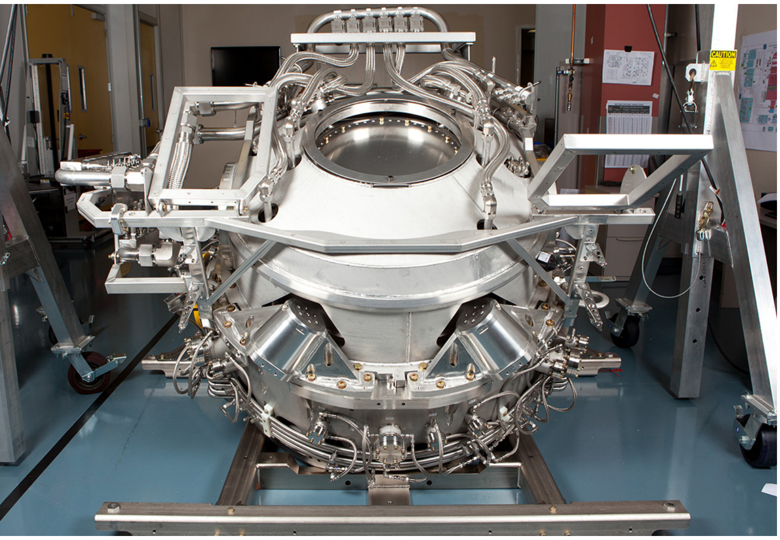
A major challenge to fielding practical LPP EUV sources has been protecting the radiation collection optics from contamination.

drilling metals and refractory nonmetals, became a reality as soon as lasers with sufficiently high powers came on the market.

But lasers have also been put to use simply to heat materials to incandescence, thereby generating a wide spectrum of electromagnetic radiation. Powerful short-pulse lasers have been used to bombard a variety of metal targets to generate both UV radiation and X-rays, such as those created by the multiple laser beamlines of the U.S. National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory in California. On a smaller scale, laser-plasma-based xenon lamps are commercially available for generating broad spectral output, from near infrared to deep into the UV region.

Starting in the 1970s, many academic and government labs tried generating DUV and even EUV radiation by bombarding elements like gold, nickel and other transition and rare-earth metals with laser beams. Similar efforts were later made with noble gases—especially xenon, which radiates a particularly rich spectrum of electromagnetic radiation on intense heating with pulsed laser beams.

The field began to develop more rapidly after work in 1981 by G. O'Sullivan and P. K. Carroll at University College Dublin, which demonstrated that irradiating rare-earth and transition-metal targets with lasers above a certain threshold pulse energy can generate strong resonance emission. These emissions, found to lie in the 4-to-20-nm wavelength range, were attributed to 4d–4f transitions taking place in multiply-charged metal ions present in the plasma. A systematic study revealed that, with increase in the target's atomic number, the peak of these narrowband emissions moved monotonically toward shorter wavelengths. O'Sullivan and Carroll also found that a tin plasma in particular emits in a very strong and narrow band centered at 13.5 nm.



A view of an EUV source vessel, showing radiation exit port.
Courtesy of ASML Lithography

The O'Sullivan and Carroll report, while of considerable scientific interest, did not spur immediate efforts to build practical EUV sources, as solid tin targets were known for generating tremendous amounts of debris on laser irradiation, and as the conversion efficiency of radiation generated from a tin target was considerably lower than that generated from a gold target. Many years later, however, the realization that the radiation produced was intense, narrowband and at a wavelength particularly suited for EUV lithography rekindled interest in tin plasma-based EUV sources. Also important was the availability of Bragg mirrors for manipulating radiation in that wavelength region—a crucial consideration, because EUV radiation cannot be handled with refractive optical elements and ordinary specular mirrors.

The tin droplet plasma source

Since then, academic and corporate labs have worked on developing practical, reliable and long-lived tin-plasma EUV sources. Those efforts have culminated in the development of modern EUV systems targeted specifically as radiation sources for semiconductor lithography (see infographic at right). They operate by irradiating a stream of tiny droplets of highly purified tin, fired at rates of several tens of thousands of droplets per second, with pulses from a CO_2 laser, within an ultra-high-vacuum chamber. The targeting of the tin droplets is controlled by a high-speed camera that monitors the droplet flow. As the laser pulses impinge on the droplets of tin, they instantly create a high-temperature plasma that radiates at EUV wavelengths. The radiation is collected by an ellipsoidal collector mirror, filtered, and transported out of the source vessel and into a scanner unit for lithographic patterning.

Such a system, demonstrated by Cymer Inc. (now a division of ASML B.V. of The Netherlands) several years ago, succeeded in generating 11 W of power at a 13.5-nm wavelength. More recent systems have demonstrated EUV output powers in excess of 250 W—a critical threshold, as it's considered the minimum viable output power for semiconductor wafer lithography in a production operation.

Ingenious solutions

A major challenge to fielding practical LPP EUV sources has been protecting the radiation collection optics from contamination. The ellipsoidal collector mirror, made from a multilayer alternating stack of molybdenum and silicon thin films, presents a large surface area inside the vacuum chamber. It sits only a few centimeters away from the location of plasma generation and EUV emission (primary focus). Its size and location make it particularly vulnerable to the contamination generated as each tin droplet is ablated by laser pulses. The interaction of high-peak-power infrared radiation from the laser with a molten tin droplet produces tin vapor and particulate matter, in addition to tin plasma; the metal vapor and particles can easily coat the collector and rapidly decrease its reflectance. Without a proper debris mitigation strategy, the collector will have to be frequently removed and replaced, making the source uneconomical to operate.

Several ingenious solutions have arisen to counter such collector contamination. For instance, at the front of the collector, a steady flow of low-pressure hydrogen gas chemically reacts with tin vapor and fine particles to create volatile tin hydride, which is removed by the normal vacuum inside the system before it can reach the collector mirror. Some sources also magnetically sweep tin ions formed in the plasma away from the collector surface. EUV sources developed by the Japanese firm Gigaphoton Inc., for instance, use superconducting magnets to direct tin ions into special collectors. As a result of such techniques, modern LPP sources require very infrequent servicing of their collector mirrors.

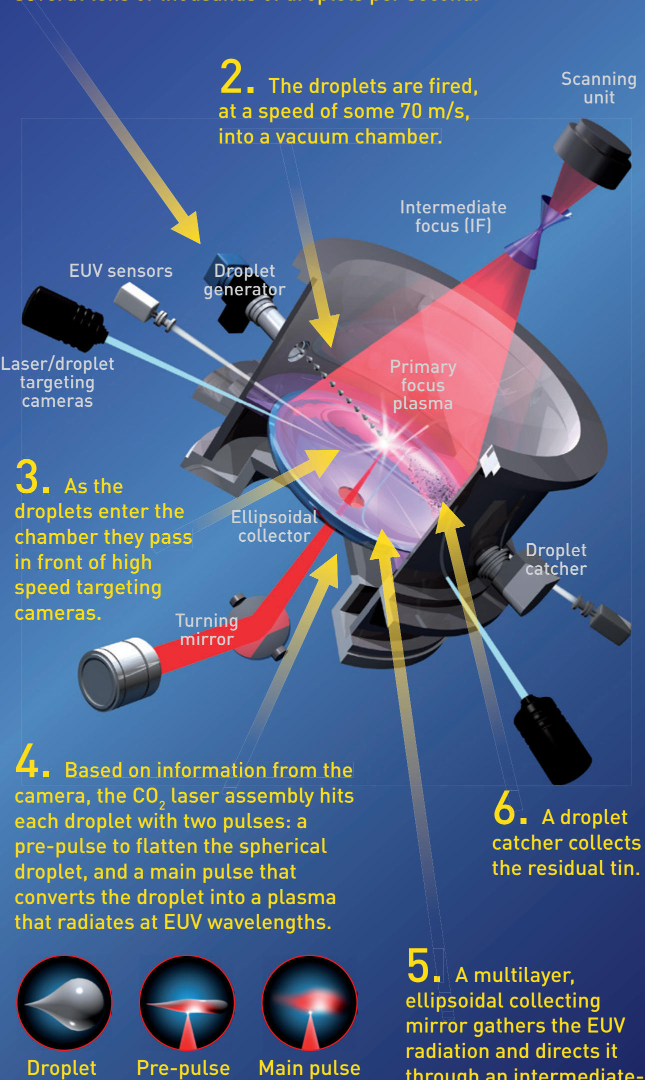
Another set of challenges relates to the characteristics of the EUV radiation itself. At these excessively short wavelengths, all materials, including ambient air, become strong radiation absorbers. Thus all optical

From LPP to EUV

Extreme ultraviolet (EUV) radiation, derived from laser-produced plasma (LPP) created from a stream of tiny tin droplets, holds a key place in plans for taking semiconductor lithography to the next level.

Here's how it works:

1. Tin is loaded into a droplet generator and converted into a stream of droplets, each around 30 microns in diameter and flowing at rates of several tens of thousands of droplets per second.



2. The droplets are fired, at a speed of some 70 m/s, into a vacuum chamber.

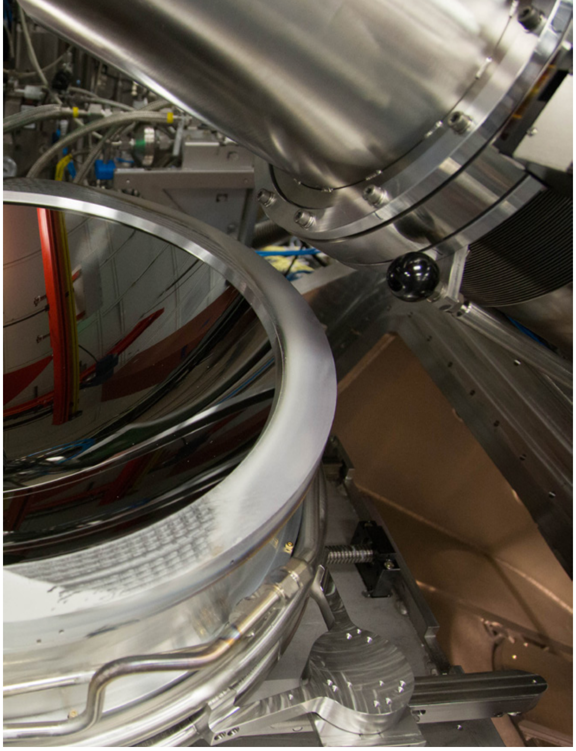
3. As the droplets enter the chamber they pass in front of high speed targeting cameras.

4. Based on information from the camera, the CO_2 laser assembly hits each droplet with two pulses: a pre-pulse to flatten the spherical droplet, and a main pulse that converts the droplet into a plasma that radiates at EUV wavelengths.

5. A multilayer, ellipsoidal collecting mirror gathers the EUV radiation and directs it through an intermediate-focus unit into a scanning unit, where additional precision optics and multilayer Bragg stack mirrors shape and bounce the beam for use in semiconductor lithography.

6. A droplet catcher collects the residual tin.

Illustration by Phil Saunders



EUV radiation collector mirror. Courtesy of ASML Lithography

manipulation in the system—from radiation collection, filtering and beam shaping to beam delivery and final focusing—must happen in an ultra-high vacuum, making exclusive use of multilayer Bragg stack mirrors.

These reflective elements are made by depositing hundreds of precisely controlled alternating layers of silicon and molybdenum, each about 3-nm thick, onto appropriately shaped substrates. (The same technique is used to make mirrors for space-based X-ray telescopes.) Because of the very short wavelengths involved, mirror surfaces need to be smooth down to $\lambda/30$ grade, which translates to around 0.45-nm RMS surface smoothness at $\lambda = 13.5$ nm.

Even with such exceptional smoothness, reflectivities of individual mirrors typically do not exceed about 65 percent. The large number of such mirrors used in a complete system means that the optical power throughput from the source to the lithography tool becomes quite small. Current EUV lithography systems typically contain at least two condenser multilayer mirrors, six projection multilayer mirrors and a multilayer-mask object. Together, these surfaces absorb more than 90 percent of the radiation delivered by the EUV source.

Thus, to enable commercially feasible high-volume manufacturing, a much larger amount of EUV power must be generated than is actually needed at the point of use. If the EUV source brightness is not increased, then the resist exposure times will become too long, leading to unacceptably low wafer throughput. Consequently, recent years have seen much effort expended toward increasing the brightness of EUV sources by incorporating a number of ingenious concepts.

As one example, it turns out that a mismatch of tin droplet size with the focused spot size of the CO_2 laser—a prominent cause of low conversion efficiency in LPP systems—can be addressed by irradiating each droplet not once, but twice. In this technique, a separate laser delivers a pre-pulse to the droplet. This distorts the droplet's shape into a flattened disk, which presents a much larger cross-section for a subsequent pulse fired from the main plasma-generating laser. That way, almost all of the power in the laser's focused spot goes to plasma generation, greatly increasing the infrared-to-EUV conversion efficiency. Without the pre-pulse, only an estimated 0.33 percent of a tin droplet is converted to the plasma phase; with the pre-pulse, up to 10 percent of the droplet ablates to form tin plasma. Shaping of the CO_2 laser beam has provided further improvements in radiative conversion efficiency.

The electric-discharge route

While LPP is by now the established approach for generating substantial amounts of EUV radiation, direct-current electrical discharge, as noted earlier, can also produce EUV energy. These so-called discharge-produced plasma (DPP) EUV sources generally cost less to build than LPP sources, but are not easily scaled to high power levels. Consequently, manufacturers of EUV sources for lithography have not generally considered DPP as a serious alternative to tin-based LPP sources.

Some companies, however, have been working on lower-power, low cost-of-ownership DPP EUV sources for niche applications that do not require large amounts of EUV power. Mask inspection and reticle metrology in EUV lithography, for instance, require low-power EUV sources of a few tens of watts. These applications can be economically served by discharge-based sources.

DPP sources of EUV radiation generally employ a pure xenon or helium/nitrogen/xenon mixture jet confined inside a ceramic capillary, inside which a high-temperature plasma is struck by high-current pulses. This configuration was first investigated at the Sandia National Labs. Several such sources, each generating a small amount of EUV power, can be combined to produce reasonably large amounts of EUV flux. Such an approach is used in a DPP EUV source, called Hydra, developed by Nano-UV.

Hydra comprises an assembly of ten individual "Cyclops" DPP cells. This system, targeted for EUV mask inspection and metrology systems, features an irradiance of 10^{18} photons/cm^2/s when all Cyclops

Now it is only a matter of time until EUV lithography, so long a promised technology, begins to enter the mainstream of the semiconductor business.

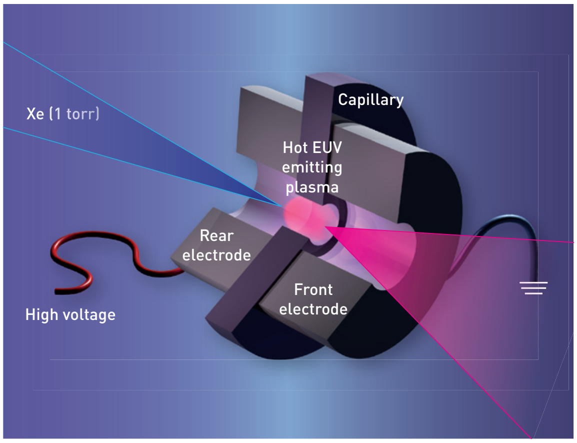
cells are operating optimally. Nano-UV's EUV source does not use a collection mirror, instead relying on spatial multiplexing (using multiple small sources) to build up radiation intensity. However, like all discharge-based radiation sources, the discharge cells are prone to electrode erosion and thus require periodic maintenance.

Ready for the future

LPP sources based on CO_2 irradiation of liquid tin micro-droplets constitute the most advanced technology for generating industrially useful amounts of EUV radiation—and those sources have made dramatic advances in recent years. ASML's 4th-generation NXE:3400B EUV lithography system, released in 2014, includes a source capable of generating 250 W of 13.5-nm EUV power at the intermediate focus. The 250-W threshold is a key one, as noted earlier, because it puts the machines in the range of practical production EUV lithography.

In a lithography operation, the EUV radiation produced at the source is then coupled to the entry port of an EUV lithography scanner. After passing through quite a few catoptric elements, relatively little EUV flux is available to project off a reflection reticle and be incident on a resist-covered wafer for actual patterning. The EUV beamline, therefore, gets increasingly photon starved as one moves from the EUV source toward the location of the resist-coated substrate. The 250-W output power threshold for EUV sources has been considered critical, because it would allow a high enough photon budget at the location of the reticle to allow for a wafer throughput of 125 wafers per hour. Although current EUV sources are bright enough to allow commercial volume manufacturing of semiconductor wafers, the push to increase the brightness of EUV sources continues to spur on further advances in EUV technology.

At present, EUV is on the cusp of introduction for mass production of 300-mm-diameter silicon wafers. For quite some time, EUV sources have undergone trials by all major global semiconductor manufacturers. Multiple EUV source/scanner units have been installed in pilot production lines at many fabs around the world. ASML reportedly shipped ten NXE:3400B systems in 2017 and has a backlog of 23 systems for future deliveries. Small-scale batch productions with R&D wafers have been very successful and chip yields are ramping up. Now it is only a matter of time—perhaps less than a year—until EUV lithography, so long a promised technology, begins to enter the mainstream of the semiconductor business. OPN



Conceptual schematic of a xenon DPP EUV generator.
Illustration by Phil Saunders / Adapted from original by Sandia National Labs, USA

Acknowledgments – I am grateful to Brittany Zatezalo and David Brandt of ASML Lithography for very informative discussions and insights into the current commercial status of EUV lithography systems.

Faiz Rahman (rahmanf@ohio.edu) is a professor of electrical engineering at Ohio University, Athens, Ohio, USA.

References and Resources

- G. O'Sullivan and P.K. Carroll. "4d–4f emission resonances in laser-produced plasmas," J. Opt. Soc. Am. **71**, 227 (1981).
- V. Bakshi, ed. EUV Sources for Lithography (SPIE, 2006).
- T. Tomie. "Tin laser-produced plasma as the light source for extreme ultraviolet lithography high-volume manufacturing: history, ideal plasma, present status, and prospects," J. Micro/Nanolith. MEMS MOEMS **11**, 021109 (2012).