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Compact X-ray and Extreme-Ultraviolet Light Sources

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Bringing the brightness and power of vast synchrotron and free-electron laser sources to the scale of the local lab and clinic marks an important next frontier—and could transform the landscape of X-ray science and technology.

Scientists have used X-rays for more than a century to elucidate matter's microscopic nature. The enormous impact of X-ray science has led to more than two dozen Nobel prizes in Physics, Chemistry and Physiology/Medicine, from Wilhelm Röntgen's 1901 Physics prize for the discovery of X-rays themselves to the 2013 Chemistry prize awarded to Martin Karplus, Michael Levitt and Arieh Warshel for "development of multiscale models for complex chemical systems." Much of this work has used the same type of X-ray tube invented by Röntgen more than a century ago.

Since the middle of the 20th century, however, new light sources including synchrotron and free-electron lasers (FELs) have dramatically expanded the horizons of X-ray science. And the X-ray community now stands at the cusp of yet another revolution—the creation of compact light sources that will bring some of the power and characteristics of today's large, intense light sources to a scale suitable for industry and academic labs. This change could transform the landscape of light-source-based scientific and technological applications, just as the transition from mainframe to personal computers transformed information science.

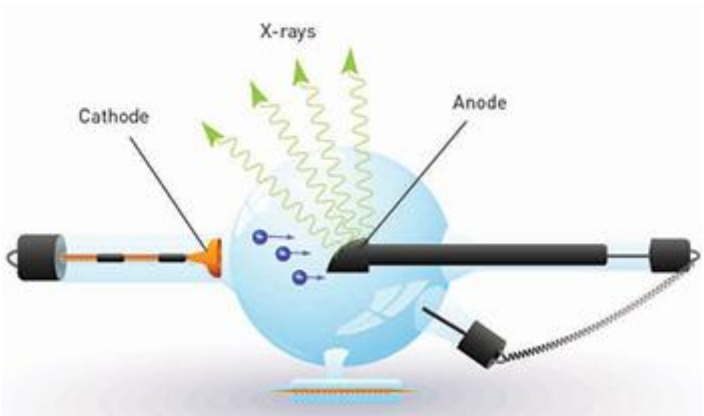
In recognition of this potential, The Optical Society (OSA) has hosted several recent international meetings to spur communication among those currently defining the future of compact X-ray and extreme-ultraviolet (EUV) light sources. This article examines the forces driving demand for these compact sources, some key types of sources discussed at the OSA meetings, and some key outcomes from the perspective of applications in semiconductor manufacturing, imaging and microscopy, and ultrafast dynamics.

Three revolutions in X-ray science

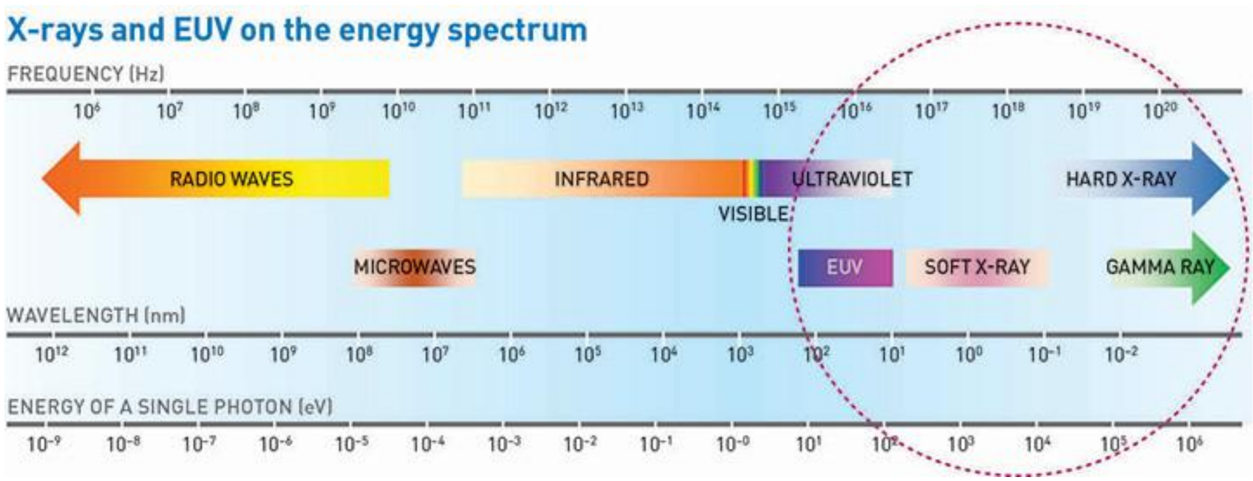
Although the X-ray tubes used in most fundamental research have undergone technological improvements since the early 1900s, their basic principle remains the same.Yet these sources lack the wavelength tunability, coherence, photon density and temporal characteristics desired in many advanced applications in medical and industrial imaging, EUV lithography, studies of time-resolved and ultrafast phenomena, and other areas. That picture has changed, however, owing to three revolutions in X-ray sources:

Synchrotron sources. The first revolution was the advent of synchrotron light sources in the mid-20th century. These relativistic electron beams carried much more power and hence produced much higher flux than conventional X-ray tubes. They also emitted the X-rays into a narrow cone because of the effects of relativity, providing a brilliance many orders of magnitude beyond what conventional X-ray tubes could generate. The scientific uses of this powerful new radiation source quickly became apparent. As a result, today, synchrotron sources are the workhorses of the X-ray scientific community, with national labs around the world supporting many kilometer-size, billion-U.S.-dollar-scale facilities that host thousands of users annually.

Free-electron lasers. The second revolution in X-ray production came with the advent of coherent emission from X-ray FELs, also based on large electron accelerators. The process of coherent emission increases the flux and brilliance of X-rays by several orders of magnitude beyond state-of-the-art synchrotrons. X-ray FEL facilities have come on line only in the last few years, but they are already revolutionizing X-ray science by enabling the study of ultrafast processes at the femtosecond scale—with the grand goal of "molecular movies" on the timescale of chemical reactions. (See P. Bucksbaum, "Sources and Science of Attosecond Light," OPN, May 2015,



In a typical X-ray tube, a voltage (about several 10,000 V) applied to a metal cathode produces a rapidly moving stream of free electrons, which generate X-rays when they are suddenly stopped by the anode (metal target) of the tube. The basic principle of such tubes has not ch anged significantly since Röntgen's 1895 discovery of X-rays. [iStock]

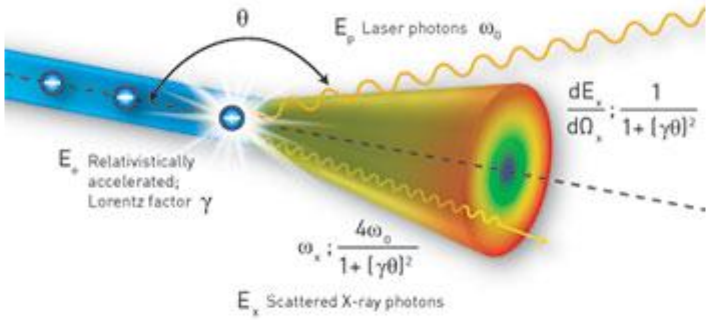


Compact light sources. Today, the X-ray community is at the dawn of a third revolution: The development of compact light sources that promise to provide intense X-rays and EUV radiation for industrial and academic labs that still rely on the relatively weak performance of the X-ray tube for research and routine tasks. This latest revolution offers the prospect of producing high-quality, short-wavelength radiation in small packages suited to a host of medical, industrial and analytical applications—and to make feasible, in a wide range of laboratories, cutting-edge experiments previously possible only at large-scale synchrotron radiation facilities. The proliferation of powerful compact X-ray and EUV sources within the wider community thus will have enormous scientific, medical and economic impact.

What is a "compact" light source?

Compact light sources range from miniature and tabletop devices to small synchrotron light sources. The development of new synchrotron storage-ring technologies, such as multibend achromatic magnetic electron beam transport systems, small-gap vacuum chambers insertion devices, and superconducting RF cavities, has made it possible to shrink the size of GeV light synchrotron sources by half while increasing their performance by orders of magnitude—so that these sources are in a sense compact, though still are relatively large facilities.

Existing truly compact light sources that fit into a normal-size room do not match the performance of the larger facilities, and in some cases may never do so. Yet several technologies could far outperform existing laboratory-scale X-ray tubes and make bright, compact EUV and X-ray light sources more accessible for use in industrial firms, medical and research labs, and educational facilities:



Inverse Compton scattering: In conventional Compton scattering, a high-energy X-ray photon scatters from an electron at rest into a lower energy photon and energetic electron. In ICS, by contrast, a low-energy laser photon scatters from a relativistic electron into a high energy X-ray photon that is emitted within a narrow angle from the direction of the electron travel. These effects are due to relativity and depend on the angle of collision (θ) and the Lorentz factor of the electron beam (γ). The process is nearly identical to undulator X-ray emission in a synchrotron. [Illustration by Phil Saunders/Adapted from F.V. Hartemann et al., Phys. Rev. ST Accel. Beams **8**, 100702 (2005)]

Inverse Compton scattering (ICS). This process, in which X-rays are created through scattering of intense laser pulses off of relativistic electrons, has long been known as a powerful source of radiation from X-rays to gamma rays. More than 20 ICS-based light sources currently operate or are under development worldwide. Some are based on a compact storage ring (as small as 2 m in diameter), others on a compact conventional or superconducting linear accelerator (LINAC). These sources typically can fit in a space measuring less than 10 m^2, and can generate X-rays from electron beams with energies ranging from a few MeV to 100 MeV, compared with the GeV beams required of large synchrotron radiation sources and FELs. The brightness of an ICS source depends primarily on the electron source brightness.

High-harmonic generation (HHG). In HHG, an intense short-pulse laser beam interacts with a gas and, through a nonlinear process, the gas emits coherent radiation at frequencies that are multiples of the laser frequency with a harmonic spectrum that is currently nearing 1 keV. Using waveguides or hollow waveguides, spatially coherent EUV beams can be generated. HHG, mainly based on high-repetition-rate Ti:sapphire lasers operating at 760 nm, is used in many laboratories worldwide. But, while very effective over a wide range of applications, HHG sources do run up against limitations in brightness, particularly in the 1-keV energy range and beyond.

Laser-driven plasma accelerators. In these sources, also called wakefield accelerators, an intense laser pulse propagates through a plasma, and the free electrons in the plasma are separated from the laser pulse by the ponderomotive force. The electrons are accelerated toward the ions in the plasma and start to oscillate about their positions, thus generating a longitudinal electron density wave, which is also called a plasma wakefield. This effect can be used to accelerate particles to very high energies, at acceleration gradients orders of magnitude greater than those of conventional accelerators, which are limited by electrical breakdown at fields around 100 MV m^{-1}. In principle, therefore, they could provide high energies at much shorter accelerator lengths and form the basis of a compact source. At present, however, driving the plasma still requires a very large and powerful laser system. Such light sources, along with those based on wakefield accelerators, have not yet made it to the laboratory, but they do show promise.

Liquid-metal-jet anode electron impact source.Enhancing the conventional microfocus X-ray tube offers another potential route to compact sources. The major obstacle in increasing the output of an X-ray tube is the dissipation of heat in the anode material. Solid anodes have to be operated below the melting point of the material or risk damage and destruction of the device. One way around this problem is the use of a liquid metal jet to enhance the output.

Which of these sources will offer the best fit for current needs and specific future applications? That question formed a key theme of OSA’s October 2014 symposium on compact sources—beginning with the promise of these sources in manufacturing.

Applications in semiconductor manufacturing

Semiconductor manufacturing can benefit from a variety of compact sources, including high-power EUV sources for wafer patterning, high-brightness EUV sources for lithography mask and wafer inspection and high-brightness hard-X-ray sources for wafer inspection and analysis.

Wafer patterning. The EUV source requirements for lithography are well understood: entry requirements are on the order of 125 W of collected EUV light, with needs quickly ramping up to 500 W. At the time of the October 2014 workshop, the technology of choice to meet initial high-volume manufacturing needs was the laser-produced plasma (LPP) source, which had demonstrated 55-W steady operation. The workshop, however, focused on a longer time horizon, in which extending EUV lithography to the 7-nm node and beyond may require in excess of 1 kW of EUV power.

In this power regime, the workshop participants were skeptical that LPP would be a viable solution. FELs appear more viable from the technological perspective, but the idea of a 1-kW FEL compatible in size with a single lithography tool did not seem a practical approach in the required time frame. Instead, the discussion focused on a larger-scale machine generating in excess of 10 kW to supply multiple EUV lithography tools in parallel. Very high-average-power FELs in the 10-kW range have been demonstrated in the infrared, but further development is needed in the UV range.

Some of the main challenges that emerged in the workshop included a required uptime of greater than 99 percent, 24 hours a day, 7 days a week, 365 days a year (with a consequent potential need for redundancy), radiation safety in commercial applications, beam distribution and coherence control, and cost of ownership.

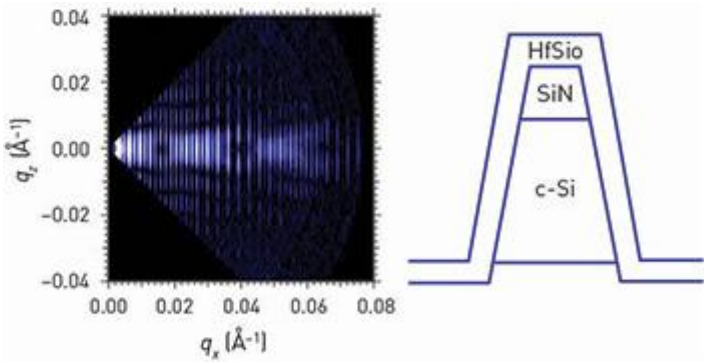
Mask qualification and inspection. The photomask, onto which a larger version of the target circuit features is patterned, serves as the master for every computer chip produced. Hence, qualification and inspection of these masks—including reflectometry, mask blank inspection, patterned-mask inspection and defect review—constitutes a critical step in the manufacturing process. Moreover, given the Bragg reflective nature of these masks, characterization at the same wavelength as used for the lithography is also essential.

The key source characteristic for mask-based applications (in contrast to wafer-patterning requirements) is brightness, not power. For reflectometry, commercial tools are available today based on small-scale LPP sources that will likely remain suitable for future needs. For mask blank inspection, the requirements are a radiance of 30 W/mm^2-sr within a 2 percent bandwidth now and greater than 60 W/mm^2-sr in the future. For patterned-mask inspection, the requirements have been documented as a radiance of greater than 20 W/mm^2-sr within a 2 percent bandwidth and a repetition rate of greater than 10 kHz. For defect review, the requirements will likely be a minimum radiance of 30 W/mm^2-sr within a 2 percent bandwidth and a pulse-to-pulse energy stability of better than 3.5 percent 3-sigma, with future targets of greater than 100 W/mm^2-sr.

Economically, sources for mask qualification and inspection will require a significantly smaller footprint and cost relative to wafer patterning sources. At present, both alternative LPP and discharge-produced plasma (DPP) sources are being developed for these applications, with first-generation DPP-based tools now operational for both mask blank inspection and defect review. Although many of the individual requirements noted above have been met with current sources, to date no single source has been able to simultaneously meet all the requirements. For example, LPP sources can meet the brightness requirements, but have challenges in terms of energy stability. Higher-stability DPP sources, however, face challenges in terms of brightness and repetition rate.

Wafer inspection. X-rays show great promise for semiconductor wafer inspection. Established techniques that remain severely source-limited in performance include X-ray diffraction, X-ray fluorescence and X-ray reflectivity. Commercially, these hard-X-ray techniques rely on rotating-anode sources. The consensus at the workshop, however, was that such sources are insufficiently bright, by one or two orders of magnitude, for full adoption in high-volume manufacturing. ICS appears to be one of the more promising technologies to meet future hard-X-ray wafer inspection needs.

Also discussed were emerging inspection techniques to characterize structure morphology and critical dimensions (CD), including transmission small-angle X-ray scattering (CD-SAXS) and grazing-incidence SAXS, which use hard and soft X-rays, respectively. In the hard-X-ray regime, CD-SAXS requires about two orders of magnitude improvement in compact-source brightness compared to rotating-anode sources. In the soft-X-ray regime, however, both X-ray laser sources and HHG sources were described as meeting brightness requirements today, with the largest challenge being in the engineering of robust turnkey systems.



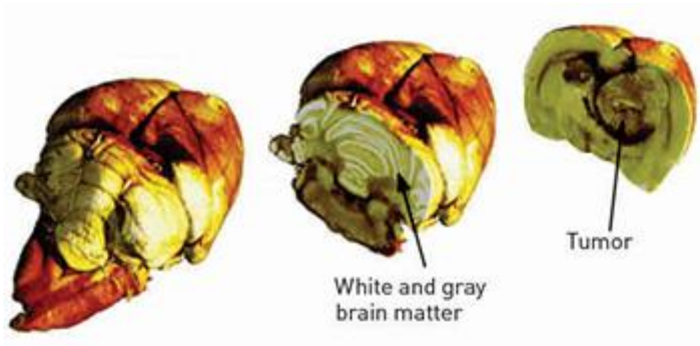
Emerging wafer-inspection techniques: New techniques such as small-angle X-ray scattering to assess critical dimensions (CD-SAXS) are gaining momentum with the emergence of compact X-ray sources. The X-ray diffraction pattern (left) yielded by CD-SAXS can characterize strongly 3-D structures such as this FinFET (right) at sub-25-nm length scales. CD-SAXS can accurately quantify the average period, height, and angles of a repetitive structure. Data taken using DND-CAT Beamline 5 ID-D at the Advanced Photon Source, Argonne. Compact sources could someday bring similar power to industry. [Courtesy of R. Joseph Kline, National Institute of Standards and Technology]

Imaging and microscopy

The advent of synchrotron radiation sources has enabled rapid development of new imaging and microscopy techniques. One example is phase-contrast imaging, which yields higher contrast and resolution and deposits a far lower X-ray dose than the traditional absorption-based contrast imaging, and therefore provides new and otherwise inaccessible information.

Compact light sources such as ICS sources are particularly suitable for this purpose, as they provide a point-like source which offers good resolution and sufficient divergence to image large specimens, while being monochromatic and tunable to reduce the radiation dose on the tissue. The ability to perform phase contrast medical imaging in a clinical setting would have several major impacts including greatly reduced radiation exposure for mammography, the ability to image arterial plaques to guide treatment of heart disease, and the ability to image injuries in soft tissue that are important to military medicine.

Biological imaging with coherent EUV/soft-X-ray sources is undergoing very rapid growth. Today, coherent sources with nJ fluence and kHz repetition rates are readily available. Future needs in this domain will require the development of compact sources with at least 5-kHz repetition rates. The “water window”—wavelengths between 2.3 nm and 4.5 nm, a range that encompasses the K-absorption edges of the building blocks of biological molecules—should be a privileged target for these applications.



Differential phase-contrast imaging: Three-dimensional images of a rat brain with tumor show potential power of this technique, which builds up 3-D volume data from multiple differential phase contrast projections using a synchrotron radiation source. ICS and other compact sources could someday bring similar power to the local research lab or medical clinic. [M. Bech et al., Z. Med. Phys. **20**, 7 (2010).]

Ultrafast dynamics

Studies of ultrafast dynamics of matter in gas, plasma and solid states hinge on the progress of source development in the EUV and soft-X-ray domain. The ideal sources for these studies should provide mJ fluence, a several-kHz repetition rate and a pulse duration of femtoseconds to picoseconds pulse duration. While the required pulse energy is a realistic goal with today’s technology, the most serious challenges relate to increasing the repetition rate and reducing the pulse duration—in particular at shorter wavelengths, in the X-ray region.

Education and training

There is an increasing interest in bringing high-quality short-wavelength radiation to university laboratories. The access to X-rays and EUV light on university campuses will greatly improve training capabilities for both undergraduate and graduate students. Closer ties and interactions among national facilities, academia and industry could further cross-training and innovation and stimulate technology transfer. The result should be a triple benefit for science. The new technology on campus will spur myriad applications in many different fields. Graduates from schools with access to the new technology will take their experience to their new employers, disseminating the technology outside academia. And the improved training will itself result in further research in compact light source technology.

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