Impact of Synchrotron Radiation on Materials Research

by ARTHUR BIENENSTOCK and ARTHUR L. ROBINSON

Synchrotron radiation has transformed the role of X rays as a mainline tool for probing the atomic and electronic structure of materials and their surfaces.

FROM THEIR DISCOVERY 100 years ago, X rays have tantalized scientists with their ability to see into solid objects. For 80 of those 100 years, they have also been our principal means of unraveling the positions of atoms in crystallized solids, from the comparatively simple structures in metals and semiconductors to the highly complex arrangements in biological molecules, such as proteins and DNA. During the last three decades, however, the growth of synchrotron radiation with its bright, wavelength-selectable X rays has markedly expanded the scope of investigation.

The result for materials research is a tool that can probe in minute detail the interior and surface of all manners of samples, large and extremely small, including noncrystalline and inhomogeneous materials.

STRUCTURE IS THE KEY

Equally applicable to semiconductors for miniaturized computer chips, superconductors to drive magnets in medical imaging machines, magnetic disks for digital data storage, metals and alloys for high-strength structures, ceramics for engines and turbines that can operate at elevated temperatures, polymers for lightweight parts for automobiles or aircraft, light-emitting materials for flat-panel video displays, biomaterials for prostheses, or any of a host of other things, the fundamental tenet of materials research is that structure determines function.* The practical corollary that converts materials research from an intellectual endeavor into a foundation of our modern technology-driven economy is that structure can be manipulated to construct materials with particular desired behaviors.

Most basically, structure means the positions of the atoms (atomic structure) and the behavior of the electrons around the atomic nuclei (electronic structure). The atomic structures of solid materials span the extremes from completely ordered with atoms arrayed around the points of a repeating lattice (long-range order) to completely disordered. Many materials, such as metals and semiconductors, have crystalline structures with long-range order but may exhibit features of disorder, such as random distributions of impurity atoms or of aggregations of atoms in the form of precipitates. In addition, the material may consist of a large number of crystalline grains with different orientations. Some materials are mixtures of grains representing different phases with distinct compositions and structures. Computer chips begin with silicon single crystals, whereas metals and alloys are typically polycrystalline. Glasses are the most familiar disordered materials.

As for the electronic structure of materials, the inner electrons are bound tightly to the atomic nuclei (core electrons) with quantum states that retain much of their atomic character, whereas the outer, more loosely bound electrons participate in chemical bonding between atoms (valence electrons), as well as other processes, such as conducting electricity. In treating the valence electrons, solid-state theorists have found it easiest to make quantum mechanical models in the case of ordered materials. In these models, a valence electron is not identified with any particular atom, but is characterized by a kind of momentum (crystal momentum) and by an energy E associated with each momentum vector k. Although the allowed energies are quantized, in practice they are quasi-continuous functions of momentum $E(k)$, giving rise to the term band structure. Band gaps refer to ranges of energies that are forbidden irrespective of momentum.

SYNCHROTRON RADIATION

X rays are particularly well suited for probing the structure-function relationship because of their ability to penetrate into materials and because of the ways they interact with the constituents once they get inside. There are two basic types of X-ray interactions, scattering and absorption, that give structural information.

The pattern of scattered radiation contains information about the spatial structure of the scattering object. Since scattering is most informative when the wavelength is somewhat less than the size of the scattering object, X rays with short wavelengths near one angstrom are ideal for investigating the positions of atoms, whereas X rays with longer wavelengths are more appropriate for larger features. X-ray absorption provides a way to study electronic structure because the energy range of X-ray photons nicely matches that needed to excite electrons from core to valence quantum states or from one band to another.** Dissipating the energy of the photoexcited electrons can have many consequences, such as the emission of electrons, photons (fluorescence), or ions from the surface, all of which give rise to spectroscopic techniques to monitor the electronic structure.

From its first systematic use as an experimental tool in the early

*The structure-function relationship applies equally well in the life sciences. See "Biological Applications of Synchrotron Radiation" in the Fall 1994 Beam Line, pp. 19–28, for a review of protein crystallography.

**The photon energy ε measured in electron volts is inversely proportional to the wavelength λ measured in angstroms according to ε [eV] = 12,398.5/λ [Å].

Aerial view of the Stanford Synchrotron Radiation Laboratory at SLAC.

1960s, synchrotron radiation has vastly enhanced the utility of pre-existing and contemporary techniques, such as X-ray diffraction and X-ray photoelectron spectroscopy (photoemission), respectively, and has given rise to scores of new ways to do experiments that would not otherwise be feasible, or even possible. Generated by electrons (or positrons) circulating for many hours at the speed of light in accelerators called storage rings, synchrotron radiation is, in the newest facilities, one billion times brighter than the light from conventional X-ray tubes. Moreover, the wavelength can be selected over a broad range to match the needs of particular experiments. Together with additional features, such as controllable polarization (both linear and circular), laser-like collimation, and pulsed time structure, these characteristics make synchrotron radiation the X-ray source of choice for such a wide range of materials research that the following examples can only give a flavor of its impact on the field.

Materials research using X rays tends to be grouped into techniques carried out at high X-ray photon energies (hard X rays) and at low X-ray photon energies (soft X rays).

HARD X-RAYS

X-ray Crystallography in Two Dimensions

Since W. L. Bragg's first determination of a crystal structure (rock salt) in 1913 by measuring the intensities of X-ray beams diffracted by the NaCl crystal, researchers have made remarkable advances in their understanding of atomic arrangements in three-dimensional crystalline solids. The high brightness of synchrotron radiation made it possible for scientists from AT&T Bell Laboratories to extend X-ray crystallography to surfaces in 1979 experiments at the Stanford Synchrotron Radiation Laboratory (SSRL). In their technique, grazing-incidence X-ray scattering (GIXS), the X-ray beam strikes the sample surface at angles close to the critical angle for total reflection. (Total reflection occurs when the angle between the incident beam and the surface is very small if the X-ray index of refraction is less than unity, as it is for most solids.) Depending on the angle of incidence, the X-ray beam penetrates from about two nanometers to several micrometers below the surface. The beam is only diffracted by the material it penetrates, so that the structures of the first few layers of a thick material or those of thin films can be determined. First applied to ordered interfaces and then to surfaces whose structures differ from that of the interior (reconstructed surfaces), the technique is now used extensively in materials research to determine the structure of oxide layers in semiconductors and magnetic materials, as well as that of thin amorphous (non-crystalline) films.
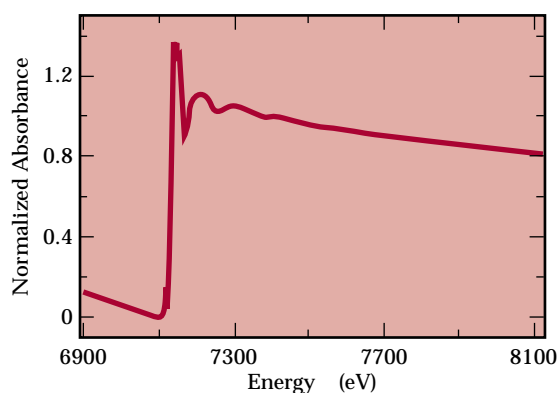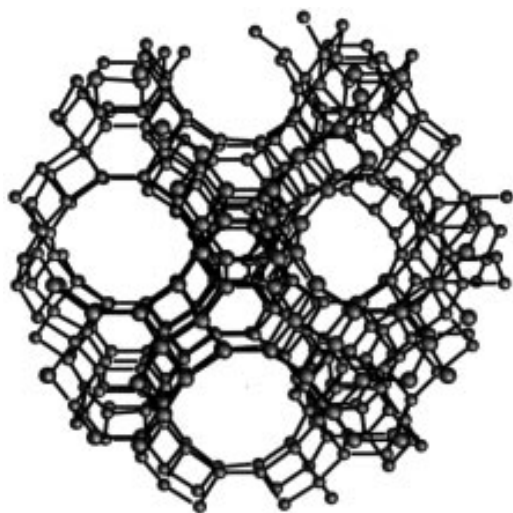
Zeolites are essential to modern industry with numerous applications, including use as ion exchanges, sorbents, separation media, and hydrocarbon conversion catalysts. They are aluminosilicates whose structures have pores and channels of molecular dimensions, as shown in the top figure. Their catalytic properties can be modified by incorporation of transition metal ions, such as Fe^{+3}. The bottom figure shows the X-ray absorption coefficient versus photon energy near the absorption edge of Fe^{+3} in iron zeolite, which was measured to determine the Fe coordination. (From work of C. M. Stanfel, K. O. Hodgson, I. J. Pickering, G. N. George, and B. Hedman of Stanford/SSRL plus D. E. W. Vaughan and K. G. Strohmaier, Exxon Research and Engineering Co.)

Sometimes, the sample itself is only one or two molecules thick, so that it is in effect a two-dimensional system where behavior can differ from that usually observed. Among the most exciting two-dimensional phenomena to be analyzed are melting and crystallization. In three dimensions, crystallization is a first-order transition with a latent heat and a well-defined melting temperature at which the material transforms from highly disordered liquid to a well-ordered crystal. But, in two dimensions, the liquid-solid transformation can be continuous over a range of temperatures. As the liquid is cooled, the maximum size of ordered regions within the liquid grows until it covers the entire sample (i.e., the range of order diverges) at the "melting" temperature. Experimental understanding of this process at the microscopic level has come primarily through the use of synchrotron radiation whose high intensity is necessary to obtain a strong signal from the extremely small number of scattering atoms and whose collimation (high angular resolution) is required to observe the divergence of the order range.

Disordered Materials and X-ray Absorption Spectroscopy

A very large portion of the matter in our world is not in the two- or three-dimensional crystalline form studied by crystallographers. Much of it is amorphous or liquid. Because such materials lack the periodicity that makes the description of crystals relatively simple, they must be described in different ways. The most important way is to determine the average environment of each atomic species in the material. For example, how many nearest neighbors, next nearest neighbors, and so on does that atom have? What species are the neighboring atoms, and what are the distances to those neighbors?

High-accuracy X-ray absorption spectroscopy, made practical by the intensity and wavelength tunability of synchrotron radiation, has provided major advances in our ability to obtain such descriptions. In this approach, one measures the X-ray absorption coefficient as a function of photon energy near an X-ray absorption edge. (An X-ray absorption edge is the energy required to knock an electron out of an atomic quantum state; each atom has a unique set of edges, some of which occur at hard X-ray and some at soft X-ray photon energies.) As shown in the illustration on the left, the X-ray absorption coefficient drops relatively smoothly with increasing photon energy until the absorption edge is reached, then it rises markedly and begins an overall decrease with increasing photon energy. Oscillations are, however, superimposed on this decrease. The sharp features closest to the edge are known as X-ray absorption near-edge structure (XANES or NEXAFS), while those oscillations continuing to about 1000 eV above the edge are known as extended X-ray absorption fine structure (EXAFS). Both reflect the influence of the atoms surrounding the absorbing atom on the absorption coefficient, although in quite different ways, so that, even in a very complicated material, one can obtain the average environment of the specific atomic

species whose absorption edge is being studied. In the same way, one can determine the average environments of the individual atomic constituents of an amorphous material.

Since XANES and EXAFS are linked to the excitation process, the photon-energy dependence of any process directly associated with the excitation can yield the fine structure and the local environmental information. Thus, the fluorescence given off by the absorbing atom (whose photon energy depends on which absorption edge is excited and, hence, is unique to each atomic species) can be used as the signal, and, with a detector that discriminates against all other photon energies, an enormous increase in signal-to-noise is obtained. This enhancement is particularly valuable when the species of interest is present in very low concentrations, such as dilute impurities in semiconductors or proteins in solution. Similarly, measurements of the photon-energy dependence of the number of electrons photoemitted from the solid are used to analyze the environments of atoms on the surfaces of materials.

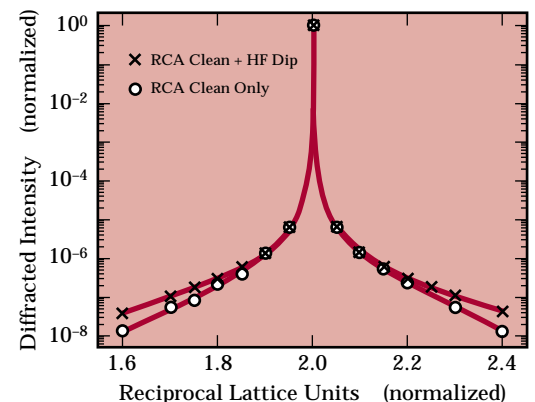## High-Sensitivity Chemical Analysis and Microcontamination

X-ray fluorescence can also be used for nondestructive chemical analysis of materials; in fact, it is the second most common use of X rays for materials research. Analysis of the photon energies at which fluorescence is emitted yields the sample's composition. With synchrotron radiation, the sensitivity of this technique has been increased markedly because of the high-
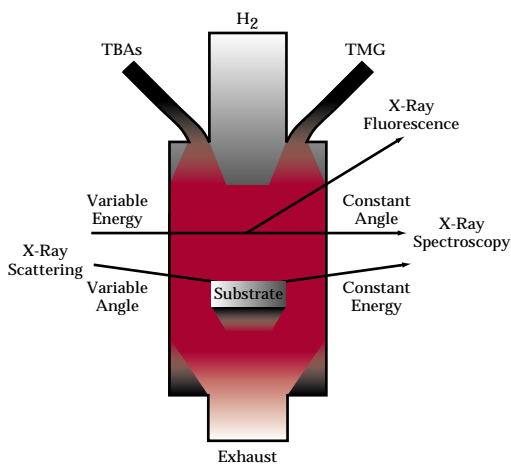
intensities and wavelength tunability. At SSRL, its first application was in response to a claim that super-heavy elements were present in some minerals. This claim had enormous significance, since the elements have higher atomic number than any that had been created in accelerators., but scientists from Oak Ridge National Laboratory detected no signal at all, thereby demonstrating that the concentrations had to be far below those claimed, if the super heavy elements were present at all.

The semiconductor industry presently uses a variant of this technique called total reflection X-ray fluorescence (TXRF) to screen the surface of polished silicon wafers for unwanted metallic and light-element impurities before microcircuit fabrication begins. Grazing incidence is used to obtain surface sensitivity, as in GIXS, and the fluorescent radiation is detected. TXRF with a conventional X-ray source is now used almost routinely, but about one hundred times greater sensitivity is required to aid in the development of fabrication processes for the high-density integrated circuits planned for the first decade of the next century, according to the Semiconductor Industry Association's (SIA) "National Technology Roadmap for Semiconductors."

Over the past two years, a collaboration of scientists from Hewlett-Packard, Intel and SSRL, with assistance from Kevex and Lawrence Berkeley National Laboratory (LBNL) staff, have achieved a fifty-fold sensitivity increase using synchrotron radiation as the X-ray source. Detector and other improvements are likely to yield the remaining factor

X-ray diffraction intensity measured over eight orders of magnitude for two silicon wafers which had previously been subjected to different cleaning procedures. Small differences in the wings of the peak, where the intensity of the diffraction is a consequence of the crystal being terminated by a surface, are being used to develop methods to characterize the effect of the procedures on the wafer surfaces. (Courtesy of A. Munkholm and S. Brennan, SSRL)

of two. Their TXRF experimental station at SSRL has now been tested by several other major semiconductor companies. This successful demonstration has resulted in TXRF with synchrotron radiation being placed on the Metrology Roadmap, a supplement to the SIA roadmap. Efforts are now under way to transform the approach from one suitable for the research laboratory to a routinely usable, consistently reliable technique. Doing so will likely also require coordination of operating schedules at two or more synchrotron sources, so that at least one is running when the other is down for maintenance.

Dynamic Processes in Solids

Synchrotron radiation beams are sufficiently bright that both scattering and X-ray absorption data can be acquired rapidly enough to follow processes as they occur in real time. For example, materials scientists are increasingly using these techniques to study dynamic processes in materials, such as the evolution of a material's structure as it undergoes physical or chemical changes, including the growth of semiconductor wafers or films prior to device fabrication and the transformation from one solid phase to another that occurs when metal alloys are heat-treated to improve their strength or ductility.

A team comprising researchers from AT&T Bell Laboratories, the IBM Research Division, and SSRL has collaborated on in-situ studies of the growth of compound semiconductors by the commercially important organometallic vapor-phase epitaxy method. Compound semiconductors,

such as gallium arsenide, offer important advantages over silicon for high-speed devices and for combining electrical and optical functions in one device.

A Stanford University/SSRL group has provided the first microscopic in-situ observations of sputtering, a common method of depositing films of myriad types. These observations made it possible to understand the relationships between sputtering parameters and the structure of the sputtered film. Scientists from the Lawrence Livermore National Laboratory (LLNL) and the University of New Mexico have observed welding-induced solid-state phase transformations using time-resolved X-ray diffraction. Depending on the situation, such transformation may be beneficial or harmful. The ability to study the dynamics of process in solids potentially represents one of the most important impacts of synchrotron radiation on materials research.

X-Ray Microtomography

Imaging has been the most important use of X rays since their discovery. Among the most dramatic recent developments in this field is computer-aided tomography (CT), in which three-dimensional images are reconstructed mathematically from absorption radiographs taken at various angles with respect to the sample. The most familiar CT application to most of us is medical diagnostic radiology, where spatial resolution is of the order of 500 micrometers. With the use of synchrotron radiation, high-resolution CT, or microtomography, is becoming

Schematic of chamber used to perform dynamic, in-situ X-ray studies of the organometallic vapor phase epitaxy production of thin gallium arsenide (GaAs) films. Organometallic vapors of gases containing arsenic (TBAs) and gallium (TMG) carry these elements to the heated substrate, where the GaAs is formed. Hydrogen transports the vapors and prepares the substrate surface. Grazing-incidence X-ray scattering is used to study the substrate and film, while the vapors are studied with X-ray spectroscopy. (Courtesy of P. Fuoss)

increasingly effective as a materials research tool, largely due to pioneering efforts by two teams, one from LLNL, Sandia National Laboratories, and the University of Dortmund and the other from Exxon. The technique now provides images with spatial resolution of the order of a few micrometers in samples with diameters less than one centimeter. One of the attributes of synchrotron radiation most critical to this improved capability is the natural collimation of the radiation, which leads to the resolution improvement. Another is the ability to select a single photon energy that is absorbed by the material of interest, which maximizes the ratio of signal to noise. These improvements have allowed detailed studies of failure in metal-matrix composites, as well as studies of the progression of osteoporosis in rats.

## SOFT X RAYS

Angle-Resolved Photoelectron Spectroscopy

The starting point for determining many of a material's properties is its band structure. Photoelectron spectroscopy has been a particularly useful way to probe the band structure of solids. Based on the photoelectric effect explained by Einstein in 1905 but developed as a useful tool only in the 1960s with the advent of ultrahigh-vacuum technology, photoelectron spectroscopy is the measurement of the spectrum of kinetic energies of photoelectrons emitted from a material after absorption of a photon (see diagram on the right). To study the band

structure, one excites the loosely bound valence electrons with low-energy ultraviolet or soft X-ray photons. An important feature of band structure that is accessible to photoelectron spectroscopy is the variation of the number of valence states with energy (the density of states). A major advance came in the mid-1970s when synchrotron-radiation researchers from AT&T Bell Laboratories developed angle-resolved photoelectron spectroscopy at the University of Wisconsin Synchrotron Radiation Center. The idea is that the momentum of the photoelectron is related to the momentum of the valence state. Measuring the direction as well as the kinetic energy gives the momentum and, hence, a way to "map" the band structure and thereby test theoretical calculations.

High-temperature superconductors provide a contemporary illustration of the usefulness of angle-resolved photoelectron spectroscopy, although the strong Coulomb and magnetic interactions in these materials make the application of conventional band structure problematic. Metallic superconductors known before the 1986 discovery of the high-temperature ceramic superconductors owe their behavior to an interaction between the valence electrons that is mediated by vibrations of the crystal lattice. The interaction usually results in a small energy gap between the superconducting and normal states that is symmetrical (i.e., the gap is the same for all momentum directions). The interaction responsible for superconductivity in the new superconductors that can operate at temperatures up to 125 Kelvin or so remains
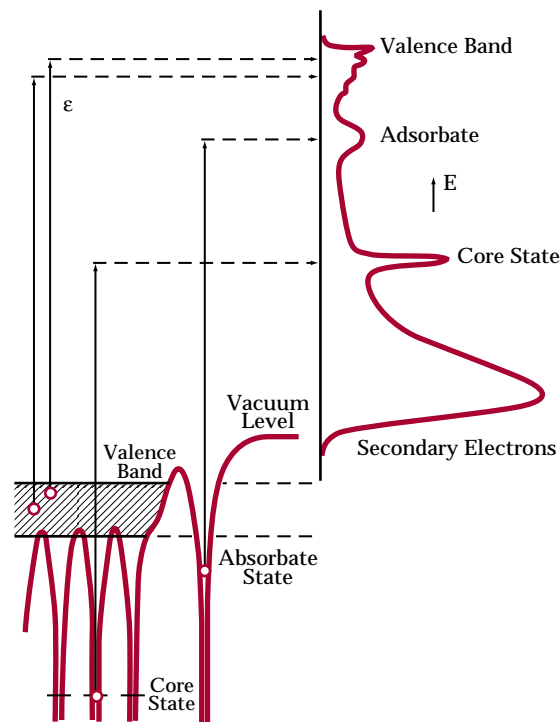
Schematic diagram of the quantum states in a crystalline solid and the photoelectron spectrum for a photon energy ε. Shown are core states in potential energy wells, the portion of a valence band occupied by electrons (cross-hatched), and a state in a potential energy well associated with the surface. The vacuum level is the minimum energy needed for a photoelectron to escape the solid. Peaks in the photoelectron spectrum occur at kinetic energies equal to the excess above that needed for the photoelectron to escape the surface. The large peak in the photoelectron spectrum at low kinetic energies is due to secondary electrons that lose energy during collisions on the way to the surface (Courtesy N. V. Smith, LBNL, and F. J. Himpsel, IBM T. J. Watson Research Center)
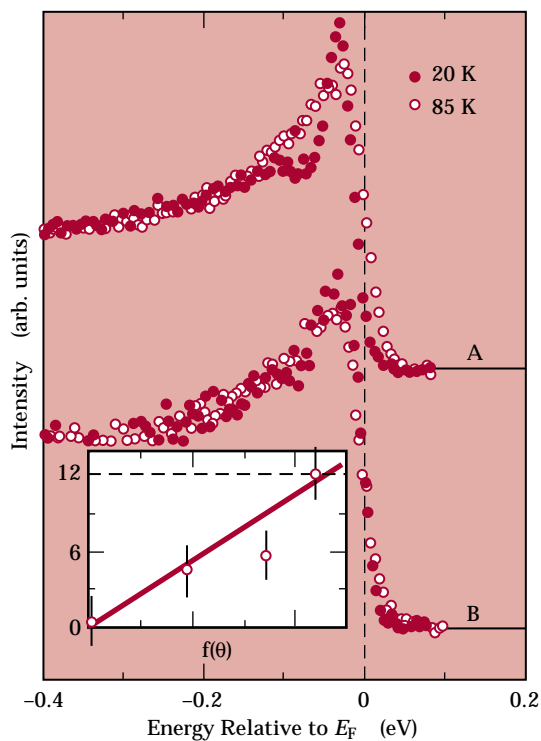
Angle-resolved photoelectron spectra for the superconducting compound $Bi_2Sr_2CaCu_2O_8$ in the superconducting (20 K temperature) and normal (85 K temperature) states for two directions of the momentum (A and B). In the super-conducting state, the appearance of an energy gap shifts the photoelectron spectrum near the Fermi energy (E_F) to lower energies in direction A but not in direction B (i.e., the gap is anisotropic). The inset shows the variation of the gap with direction in the surface plane as represented by an angular function $f(\theta)$ chosen for ease of comparison with theory. (From work of Z.-X. Shen, W. E. Spicer, and D. M. King, Stanford University; D. S. Dessau, SSRL; and B. O. Wells, Massachusetts Institute of Technology)

controversial, but recent angle-resolved photoelectron spectroscopy measurements reported only last year by a Stanford University group working at SSRL have now shown that the energy gap is strongly anisotropic, thereby narrowing the theoretical options (see figure at left).

Photoemission From Surfaces and Interfaces

X rays can penetrate deeply into a solid before being absorbed, so that a putative photoelectron has some distance to travel in order to escape from the surface. The probability of escaping with no energy losses depends on the kinetic energy of the photoelectron, reaching a minimum of a few angstroms. Experimenters using synchrotron radiation can therefore tune the X-ray photon energy to produce photoelectrons from very near the surface or deeper in the bulk, a feature that turns photoelectron spectroscopy into a surface-sensitive technique. However, while clean surfaces prepared in the laboratory often have long-range order, surfaces in the "real-world" may by design or otherwise be harder to characterize. Photoelectron spectroscopy from core states is well suited for probing short-range order and local properties (e.g., atomic coordination and oxidation states) that can be studied in these circumstances. Of particular interest, the energy of core states has a simple relation with chemical properties, such as the type of chemical bond, that depend on the local environment.

An important example is analysis of the processing of computer chips, which involves complex surface chemistry. Patterns in advanced integrated circuits are etched into a silicon surface by the process of plasma etching. In this process, a fluorocarbon plasma removes silicon fluoride molecules from the surface. There are many process parameters that have been optimized empirically, but the physical reasons for choosing them are unclear. In the mid 1980s, researchers from the IBM T. J. Watson Research Center investigated the interaction of fluorine atoms with well-prepared and characterized silicon surfaces in experiments at the National Synchrotron Light Source (NSLS). The group demonstrated that removal of the molecule silicon trifluoride is a bottleneck in the etching reaction, independent of crystallographic orientation and other parameters, a fact that was not known before this work (see diagram on next page). They have since extended their use of core-state photoelectron spectroscopy to investigate how silicon dioxide forms on silicon surfaces, another crucial process in chip manufacture.

Spectroscopic Imaging

Inhomogeneity is a fact of life for materials that aspire to work in the real world. Materials scientists deliberately mix in additives, which may be distributed unevenly, to improve the performance of metals and alloys, superconductors, permanent magnets, and ceramics. Even computer chips based on single crystals of silicon have circuit patterns made of other materials imprinted on them. To examine materials on a local scale rather than measuring an average over the entire sample, it is

necessary to have spatial resolution. With focused synchrotron radiation it is possible to direct enough photons into a small area of the sample to generate a useful signal. The most intuitive means of obtaining spatially resolved spectra is by rastering the spot across the sample (or the sample through the spot). Most of the usual photon and electron spectroscopies can be done in this way with a spatial resolution limited by the spot size. Alternatively, larger sample areas can be illuminated and imaging achieved by photon or electron optics. In either the scanning or the imaging mode, the new terms spectromicroscopy and spectroscopic imaging have been coined to describe this capability.

Polymer blends are a case in point. Designed in the hope of obtaining the high performance of expensive materials at a lower cost, blends often exist in discrete domains or phases with different compositions. Morphological features, such as domain size, presence of inclusions, and interparticle distances, are important determinants of the mechanical properties of polymer blends. Experiments in 1992 with a scanning X-ray microscope at the NSLS provide dramatic evidence for a new and direct means for investigating the morphology of polymer blends. With spatially resolved near-edge X-ray absorption spectroscopy (micro-XANES) involving chemically sensitive core states, the researchers were able to image the structure of polymer blends, including the visualization of domains several micrometers in diameter corresponding to regions of different composition and various other features, such as inclusions and holes. More recent experiments have extended the technique to still smaller structures in other types of polymers. The ultimate spatial resolution has not been reached but may eventually be better than 100 angstroms in newer facilities.

Circular Polarization

The use of circularly polarized synchrotron radiation is now at the cutting edge of research on properties that are dependent on electron spin, such as the magnetic properties of solids and thin films, a subject not only of academic interest to solid-state physicists and materials scientists but also of considerable economic importance to the magnetic recording industry. Spin-dependence is at the core of understanding magnetism on a microscopic scale. For magnetic materials, the opportunities range from development of a basic understanding that can have the same impact on the development of magnetic materials as band theory has had on semiconductors, to applications-oriented areas associated with the properties of magnetic memory and recording devices. Magnetic circular dichroism (MCD) spectroscopy, which is essentially the difference between the absorption of left- and right-handed polarized photons by a sample in a magnetic field, is the key for probing magnetic materials.

Although MCD experiments based on core-state X-ray absorption were reported first in Germany in 1987, effective use of soft X rays for the investigation of magnetic materials containing transition metals
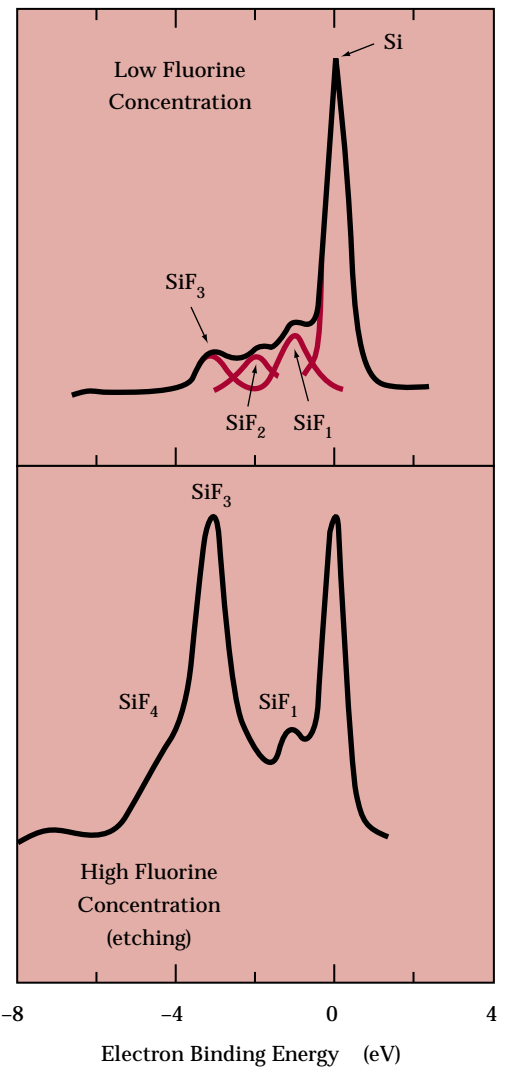
Photoelectron spectra for silicon exposed to a low and a high concentration of fluorine. The energy of the silicon peak depends approximately linearly on the number of fluorine atoms bound to silicon at the surface. The large peak due to silicon trifluoride in the spectrum for high fluorine exposure, which simulates a plasma etching environment, indicates that removal of this molecule from the surface is the bottleneck of the etching reaction. (From the work of F. R. McFeely, J. F. Morar, G. Landgren, F. J. Himpsel, and N. D. Shinn, IBM T. J. Watson Research Center)
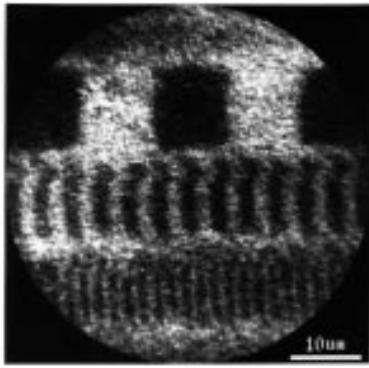
(particularly iron, cobalt, and nickel) was pioneered by an AT&T Bell Laboratories group. Thin films containing multiple layers of magnetic and non-magnetic elements, which are under intense investigation as candidates for future high-density magnetic storage materials, illustrate the usefulness of MCD. By tuning the photon energy to the element(s) of interest in each layer, the researcher can select which layer to probe. The AT&T group and its collaborators, for example, reported in 1993 experiments at the NSLS the ability to measure separately the magnetization of each layer as a function of applied magnetic field (hysteresis curves), as well as detect interactions between layers not observable by conventional techniques (see bottom illustration). Hysteresis curves are the most fundamental characterization of a magnetic material, yielding the magnetic moment giving rise to the magnetization and other information.

Spatially resolved MCD spectroscopy is called magnetic imaging. A group including researchers from the IBM Almaden Research Center and the University of Wisconsin Synchrotron Radiation Center working at SSRL graphically demonstrated the virtues of magnetic imaging in 1993 experimenters on a commerical magnetic recording disk, basically a cobalt-platinum-chromium alloy covered with a thin protective layer of carbon and lubricant. Using MCD from core states in the cobalt to provide the contrast for a microscope using electron optics to image electrons from the surface, the experimenters made images of the pattern of magnetic domains (bits) on the data-storage disk (i.e., domains magnetized in one direction had a large positive MCD signal, whereas the domains magnetized in the opposite direction had a large negative signal).

NEW CONSTRUCTION DEMONSTRATES IMPACT

If there were any doubts about the value of synchrotron radiation, the current worldwide spurt in building new facilities—including in the U.S. the Advanced Light Source at LBNL and the Advanced Photon Source at Argonne National Laboratory with a combined cost exceeding $900 million—should put them to rest (see "Third-Generation Synchrotron Light Sources" in the Spring 1994 *Beam Line*, Vol. 24, No. 2, pp. 17–28). Even with dozens of beamlines guiding synchrotron radiation simultaneously to as many waiting experiments at each facility, the demand for beam time shows no sign of leveling off. In the more distant future, there is the possibility of using electron linear accelerators to make XP-ray lasers that generate very powerful coherent beams.