Imaging in Materials Science

Guest Editor, Stephen J. Pennycook

Imaging is about communicating. Through images, it is possible to convey information about a subject in an exceedingly efficient manner. We are all familiar with the nightly news reports and how a few visual images can rapidly convey a deep impression far beyond that of the accompanying spoken word. The worlds of art and photography are based on images and their power to invoke a sense of beauty and awe in our minds. Both of these aspects are also important for imaging in materials science, although the beauty and awe we wish to convey concerns our understanding of the behavior of materials or the laws of physics and not the aesthetic appeal itself.

An image can convey an insight into a materials problem which is unrivaled in depth and breadth. In many cases, it can reveal aspects of the problem which were completely unforeseen. An image may even reveal the key to the entire problem and so provide a fundamental advance in our understanding, in contrast to the incremental advances which usually result from more or better data. It is this theme which links the articles in this issue of the *MRS BULLETIN*. Covering semiconductors to cement, the atomic scale to the macroscopic, the theme in common is the power of the image to unravel the story. Often this involves changing our preconceived ideas on the subject (images provide constant proof that "truth is stranger than fiction"), but this is what major advances in research and development are all about.

In recent years, the most spectacular example of this process has been the development of the scanning tunneling microscope by Gerd Binnig and Heinrich Rohrer, which was rewarded by the Nobel Prize for physics in 1986. The atomic-scale behavior of surfaces and their defects was suddenly revealed in tremendous detail, and the process of crystal growth, the roles of surface dimerization and surface steps, became understood at a whole new level of complexity. Robert J. Hamers gives us the flavor of this in his article "Atomic-Scale Imaging with the Scanning Tunneling Microscope."

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Also recognized in the Nobel Prize mentioned above was the development of the transmission electron microscope (TEM) some 50 years earlier by Ernst Ruska. Development has been continuous throughout the intervening half century, measured most obviously in terms of its ultimate resolution, although only in the last decade has the resolution improved to below the typical interplanar spacings of all the important classes of materials. Recently, therefore, there has been considerable excitement and much insight into materials provided by the TEM as described in the article by J.M. Gibson. He also points out another basic truth, that the more ways you look at something, the more information you get, and that coupling the high-resolution image to diffraction or other information obtained from the TEM and by other techniques can significantly refine the interpretation.

The first microscope, in fact, to resolve individual atoms was the scanning TEM (or STEM) invented by Albert V. Crewe in the late 1960s. As an imaging device, it has been applied mostly to the biological sciences, its application to materials science being principally as a high-resolution microprobe. Recently, however, the STEM has demonstrated an exciting potential for the high-resolution imaging of materials. As distinct from the Fourier reconstruction represented by the traditional TEM techniques, the Z-contrast method provides an image which can be thought of as a direct image of the atomic structure and atomic number (Z). In many cases, the image immediately conveys the atomic-scale details of the sample, and again we find that these are not always in accord with our previous notions, as described in the article by D.E. Jesson and S.J. Pennycook.

The more familiar scanning electron microscope (SEM), which images bulk material, has also evolved significantly in recent years, notably in the use of very low beam voltages, for example, in the nondestructive imaging and evaluation of semiconductor device structures. One radically new design in particular is opening up fields of materials research which so far have been completely inaccessible to imaging. Called an environmental SEM, it allows taking images during a wide range of gas-solid and liquid-solid reactions. This advance is described in the article by K. Sujata and Hamlin M. Jennings with particular application to the study of cement paste microstructures.

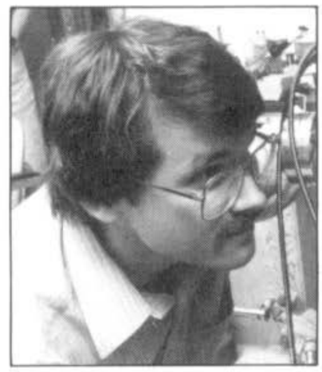
Scanning Auger microscopy is a fairly obvious extension to scanning electron microscopy, but many other surface spectroscopies can be used as the basis for imaging, as described in the article by Michael J. Kelley. In many instances, an interaction of low cross section is used, which, although necessarily limiting the available resolution, can allow exceptional sensitivity, such as the ability to image the distribution of a specific charge state of a specific element on the surface. Again, through images we obtain insight which would be difficult or impossible to obtain by other means.

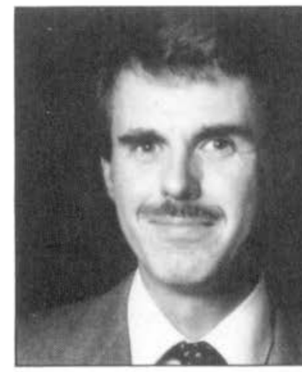
Electrons are featured very prominently in these techniques, either as the probe or as the signal detected or both. They are easily focused and scanned, and, being relatively light, many electrons can interact with an atom before it is displaced. Neither ions nor photons have both these properties. Electronics, and the personal computer in particular, have also facilitated advances in imaging. Collecting, processing, storing, and analyzing the vast array of data represented in an image is no longer a serious problem, so that imaging is increasingly replacing traditional spectroscopy. In a few years, we are even likely to see the traditional hallmarks of TEM, the photographic plate, the viewing screen, and the binoculars replaced by a digital imaging device. Trends such as these are expected in all areas of materials science.

I hope these articles will illustrate how each technique provides its own insights on its own scale, although, of course, maximum progress will result from the judicious combination of various techniques—another example of the value of the interdisciplinary approach. The power of imaging lies not just in providing and communicating the answer efficiently but also in helping researchers formulate the right questions in the first place. Much of the excitement of imaging lies in the chance that the next image will provide the insight to solve the problem. □

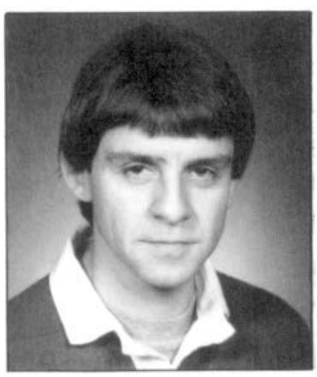

Stephen J. Pennycook


J. Murray Gibson


Robert Hamers


Hamlin M. Jennings

Stephen J. Pennycook, Guest Editor for this issue of the *MRS BULLETIN* is a senior research scientist in the Solid State Division at Oak Ridge National Laboratory, Oak Ridge, Tennessee, and leader of the Electron Microscopy Group. He obtained a PhD in physics from the University of Cambridge, England, in 1978, moving to Oak Ridge in 1982. His main research interests are the study of artificially structured and modified semiconductors and superconductors through the technique of Z-contrast STEM, the development of which earned him the 1989 Department of Energy award for outstanding scientific accomplishment and an R&D 100 award in 1990. Pennycook is a member of the American Physical Society and the Materials Research Society and is a meeting chair for the 1992 Fall MRS Meeting.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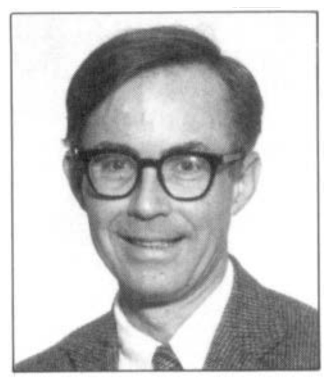
Michael J. Kelley


K. Sujata

J. Murray Gibson is currently a professor of physics and materials science at the University of Illinois in Urbana-Champaign. Until very recently he was head of the Electronics and Photonics Materials Research Department of AT&T Bell Laboratories in Murray Hill, New Jersey. He holds a PhD in physics from the University of Cambridge, England, and worked briefly at IBM Research in Yorktown Heights prior to his 10-year stint at Bell Labs. His research interests are in the field of transmission electron microscopy of semiconductor interfaces and surfaces, especially *in-situ* experiments on growth and surface gas-reactions, and recently in electron lithography. He was awarded the Burton Medal of the Electron Microscopy Society of America in 1986. Gibson is a Fellow of the American Physical Society and a Councillor of the Materials Research Society.

Robert Hamers received a BS in chemistry from the University of Wisconsin-Madison and a PhD in chemistry from Cornell University. After five and a half years on the research staff at the IBM T.J. Watson Research Center, he recently joined the University of Wisconsin-Madison as associate professor of chemistry. His research interests include scanning tunneling microscopy and related techniques, atomically resolved surface chemistry, nanometer-scale characterization of semiconductors, and optical interactions at surfaces.

Hamlin M. Jennings is an associate professor of civil engineering and of materials science and engineering at Northwestern University. He received his BS in physics from Tufts University in 1969 and his PhD in Materials Science from Brown University in 1975. Since then, he has carried out research at the University of Capetown and at Imperial College, London, where he was a lecturer until 1985. Additionally, he has served as director of research of the National Cement and Ceramics Laboratory since September 1990. He is interested in ceramics which form from reactions that occur between solids and liquids or solids and gases. Jennings' major interest is in cement-based materials.

David E. Jesson received his PhD in physics from the University of Bristol, England, in 1987. As a senior research scientist for the National Institute of Materials Research in South Africa, he received the Electron Microscopy Society of Southern Africa annual award three times. He is presently working in the Solid State Division of Oak Ridge National Laboratory, where his research interests include the development of Z-contrast scanning transmission electron microscopy and its application to understand the atomistic processes of semiconductor growth. He is a member of the Electron Microscopy Society of America and the Materials Research Society.

Michael J. Kelley received a BS degree in physics from Rensselaer Polytechnic Institute, Troy, New York, in 1966. After receiving his PhD in materials engineering from the same institution in 1973, he joined Du Pont. A senior research associate in the Engineering Technology Laboratory, he specializes in the materials science of surfaces and interfaces, with emphasis on the chemical processes occurring there and resultant applications in processing, catalysis, and composites. He is also a member of the off-campus faculty in the Chemical Engineering Department at the University of Delaware, where he teaches two graduate courses and supervises graduate students. Kelley chairs the MRS Membership Committee.

K. Sujata is currently employed by the National Cement and Ceramics Laboratories. She received her PhD in materials science from Northwestern University, and her research interests include cement in hydration, microstructural design and defect chemistry of transition metal oxides. □