Multilayer Materials

Troy W. Barbee Jr., Guest Editor

Multilayers, as considered in the following articles, are manmade thin-film materials periodic in one dimension in composition or in composition and structure. This composition/structure variation is generated during synthesis, which is typically accomplished using atom-by-atom technologies. Individual component layers in a multilayer may vary in thickness from one atomic layer (~2 Å) to hundreds of atomic layers (~1,000 Å) of a given material.

An example of these synthetic microstructures, a lattice image transmission electron micrograph of a cross section of a hundred period titanium (63 Å)/titanium-nickel (40 Å) multilayer microstructure fabricated using magnetron sputtering, is shown on the cover of this issue of the *MRS BULLETIN*. The titanium-nickel layers are amorphous as a result of the low substrate temperature (<75°C) and the very large atomic quench rates characteristic of vapor deposition ($>10^{12}$ K/s). The elemental titanium layers are fiber textured with the basal plane of this hexagonal close-pack structure element in the plane of the layers. These (00.1) planes are the ones lattice imaged in this electron micrograph.

The general concept of a multilayer structure, as illustrated above, is now well accepted because the ability to synthesize such materials for scientific study and technological application has been demonstrated at many nationally and internationally based laboratories. Though the most visible of such materials are semiconductor superlattices formed using molecular beam epitaxy (MBE) techniques, the articles in this issue focus on multilayers synthesized from materials composed of elements from all parts of the periodic table. At this time multilayer structures have been synthesized using at least 75 of the 92 naturally occurring elements. Most research work has been done with multilayer structures in which intra-layer atomic interactions have determined the structure and properties of those layers, although very small period structures (~20 Å) in which inter-layer atomic interactions are important have shown new and intriguing structures and properties.

Studies of this new class of materials include all those characteristic of materials science and engineering and solid state physics research and development, and also extend into an increasing number of scientific disciplines and technological arenas. This breadth of investigation results from the ability to synthesize materials having microstructures not found in nature—new dimensional regimes in solids are accessible and hence new science and technology are created. Additionally, multilayer structures can be synthesized using elemental, alloy, or compound layers to form both microstructures and combinations of elements/materials that cannot be produced using traditional processing approaches, again creating new opportunities.

The growth of multilayer materials into a significant area of activity is based on efforts in synthesis or fabrication, in characterization of structure and composition, and in property measurement. Inherent to the interplay of these areas of investigation is a primary materials research activity—the development of an understanding of the relationships between synthesis, resulting structure/microstructure, and properties. The dynamics of such interdisciplinary and intradisciplinary processes are clearly seen in the articles presented here, which explore three different areas that multilayer structures have impacted:

- "Metastable Phase Formation in Thin Films and Multilayers," by B.M. Clemens and R. Sinclair;
- "Artificially Layered Superconductors," by I.K. Schuller, J. Guimpel, and Y. Bruynseraede; and
- "Multilayer Optics for the Soft X-Ray and Extreme Ultraviolet," by T.W. Barbee Jr.

If a multilayer material is composed of individual layers four atomic planes thick, half the atoms in one layer are in contact with atoms of the other layer—*half the atoms in this structure are interfacial atoms*. Hence, these materials may differ significantly from bulk materials of the same composition and may exhibit new and useful characteristics as well as forming new and unexpected phases. This is the emphasis of the contribution by professors B.M. Clemens and R. Sinclair of Stanford University, who examine the effects of the large interfacial areas in multilayers and describe many of the new and interesting materials aspects of multilayer structures.

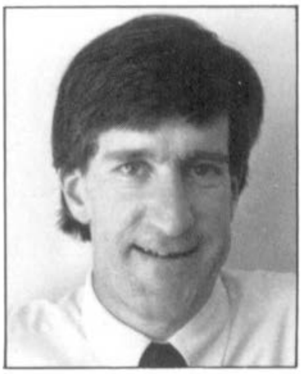
The dimensional control available with multilayer structures facilitates the fabrication of samples in which the characteristic multilayer structural length, the multilayer period, may be made of the same order as lengths characteristic of nonlocal physical phenomena in solids. Samples having such correlated physical structure/physical phenomena scales allow unique studies of the basic physical mechanisms of nonlocal phenomena and strikingly powerful tests of theory. The article by I.K. Schuller, J. Guimpel, and Y. Bruynseraede reviews how this approach has been applied to the study of superconductivity and shows that unexpected physics should be expected when such new and unique materials are available.

These layered materials are, if perfect, equivalent to single crystals in one dimension. Thus, the multilayer acts as a superlattice diffracting longer wavelength radiation in a manner directly analogous to the diffraction of x-rays by crystals. It is interesting to note that this application of multilayer structures as dispersion elements for soft x-rays and extreme ultraviolet radiation was the impetus for the first attempts to synthesize multilayer materials. The current status of this application, multilayer structures as soft x-ray and extreme ultraviolet optics, is considered in the article by T.W. Barbee Jr.

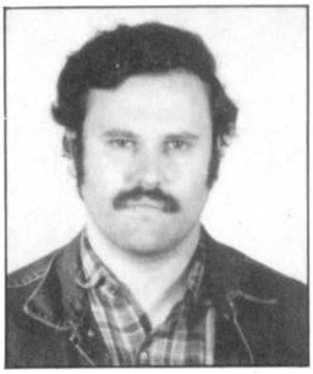
In a very real sense the articles featured here describe the threshold of a new period in materials science and engineering—that of placing more of the responsibility for creativity on us as scientists and engineers. We are no longer limited to combinations of elements allowed (by nature) to form structures dictated by the small differences in the forces between atoms and the free energies in condensed matter that define equilibrium form. This breadth of capability demands that such research be both interdisciplinary and transdisciplinary with physical experimentalists, computational experimentalists, and theorists both providing guidance for and being guided by one another. □

Troy W. Barbee Jr.

Yvan Bruynseraede

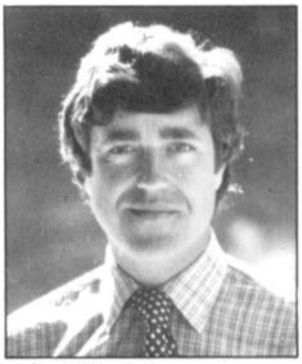


Bruce M. Clemens



Julio Guimpel

Ivan K. Schuller



Robert Sinclair

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Yvan Bruynseraede is a professor in the Department of Physics at the Katholieke Universiteit-Leuven, Belgium. He is a member of the Belgian Academy of Sciences, president of the Belgian Physical Society, chairman of the Low Temperature Section of the European Physical Society and coordinator of the Interdisciplinary Center for Superconductivity in Leuven. Over the past 10 years, he has developed a sizeable research program focused principally on low and high T_c superconductivity, magnetic interactions, electron localization and metal-insulator transitions in thin films, multilayers and mesoscopic systems.

Bruce M. Clemens, an assistant professor in the Department of Materials Science and Engineering at Stanford University, joined the Stanford faculty in February 1989. He received a BS degree in engineering physics from Colorado School of Mines and a PhD in applied physics from Caltech. Clemens' research spans thin metal films, interface reactions, multilayers and superlattices. He is interested in structural, magnetic, superconducting, and mechanical properties of these materials. In addition to metal thin films, he has recently investigated high T_c superconductors and semiconductor superlattices. He is a member of APS, TMS and MRS.

Julio Guimpel received his Licenciado en Fisica and PhD from the Instituto Balseiro (Universidad Nacional de Cuyo and Comisión Nacional de Energía Atómica), Argentina. Currently on leave from the Low Temperature Laboratory at the Centro Atómico Bariloche, Argentina, he is a postdoctoral researcher at the University of California, San Diego. His research interests have focused on the superconducting and transport properties of amorphous materials, metallic multilayers and ceramic superconductors.

Ivan K. Schuller is a professor of physics at the University of California-San Diego and a special term appointee at Argonne National Laboratory. He received his Licenciado en Ciencias from the University of Chile and his MS and PhD from Northwestern University. Schuller's research focuses on the physics and applications of thin film and layered materials, including high T_c superconductors. With colleagues at Argonne he received the Department of Energy's 1987 award for Outstanding Scientific Accomplishment in Solid State Physics for determining the structure of $YBa_2Cu_3O_7$ high T_c superconductor. He is a fellow of APS and a member of MRS and the Chilean Physical Society. He has helped organize several national and international conferences and the symposium on interfaces, superlattices and thin films at the 1986 MRS Fall Meeting. As secretary/treasurer of the APS International Physics Group he is involved in promoting international scientific cooperation.

Robert Sinclair is a professor of materials science and engineering at Stanford University. His research involves the development and application of high resolution electron microscopy (HREM) to problems in materials science, particularly emphasizing the structure and reactions at semiconductor interfaces. This work has increasingly involved interpretation of behavior using thermodynamic principles. In addition, his group has introduced hot-stage HREM for studying reactions at the atomic level. His degrees are in materials science from Cambridge University.