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ENCYCLOPEDIA ARTICLE

Artificially layered structures

Manufactured, reproducibly layered structures having layer thicknesses approaching interatomic distances. Modern thin-film techniques are at a stage at which it is possible to fabricate these structures, also known as artificial crystals or superlattices, opening up the possibility of engineering new desirable properties into materials. In addition, a variety of problems in solid-state physics can be studied which are otherwise inaccessible. The various possibilities include the application of negative pressure, that is, stretching of the crystalline lattice; the study of dimensional crossover, that is, the transition from a situation in which the layers are isolated and two-dimensional in character to a situation in which the layers couple together to form a three-dimensional material; the study of collective behavior, that is, properties that depend on the cooperative behavior of the whole superlattice; and the effect and physics of multiple interfaces and surfaces. These structures serve as model systems and as a testing ground for theoretical models and for other naturally occurring materials that have similar structures. For instance, ceramic superconductors consist of a variable number of conducting copper oxide (CuO_2) layers intercalated by various other oxide layers, and therefore artificially layered structures may be used to study predictions of the behavior of suitably manufactured materials of this class. A variety of applications have also been proposed or discovered. Of course, one of the most exciting prospects is the discovery of new, as yet unpredicted phenomena. For a discussion of semiconductor superlattices See also: Crystal structure; Semiconductor heterostructures

Preparation

Artificially layered structures have been prepared since the beginning of the century, using mostly chemical methods for deposition. With the advent of sophisticated high-vacuum preparation techniques, there has been a significant increase in activities in this field since the early 1970s. The preparation techniques can be conveniently classified into two groups: evaporation and sputtering. In an evaporation system, two or more sources of particles (which end up being part of the final structure) are aimed at a heated substrate where the artificially layered structure is grown. The rates are precisely controlled by using rate monitors, and the various beams are chopped by using shutters in various configurations. The ultrahigh-vacuum (UHV) version has been commonly designated as a molecular beam epitaxy (MBE) apparatus. The sputtering method relies on bombarding targets of the proper materials with an inert gas, such as argon, thus producing the beams of the various elements. Commonly, in this case, the substrate is held against a rotating, heated table and so moved from one beam to the next. See also: Crystal growth; Molecular beams; Sputtering

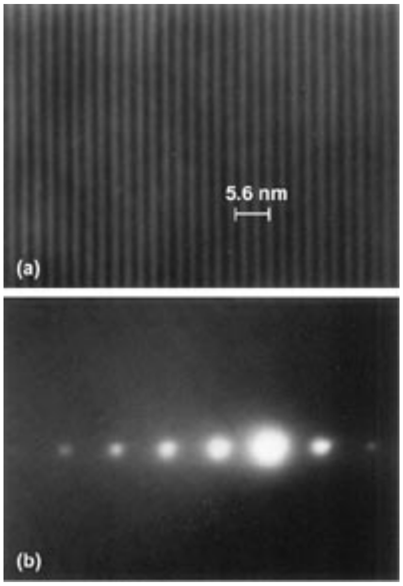

Fig. 1 Ordered superlattice consisting of alternating layers of gallium arsenide (GaAs) and aluminum arsenide (AlAs), each four atomic layers thick, deposited by molecular beam epitaxy. (*a*) Transmission electron micrograph of the superlattice. *(b)* Electron diffraction pattern of the superlattice. New diffraction spots around the central diffraction peak are the result of Bragg scattering from the long periodicity of the superlattice. (*From P. M. Petroff et al.*, *Crystal growth kinetics in* ($GaAs)_n$-$(AlAs)_m$*superlattices deposited by molecular beam epitaxy*, *J. Cryst. Growth*, *44:5–13, 1978*)

Structure

Once the artificially layered structure is prepared, it is necessary to characterize whether the layer structure is stable at the growth temperature. This is of considerable importance, since the interdiffusion of the constituents in many cases eliminates the layered growth. A direct image of the layers in gallium arsenide–aluminum arsenide superlattices, using electron micrography, is shown in **Fig. 1**. One of the most successful methods of characterizing layered growth has been x-ray diffraction. In this method the intensity of x-rays elastically reflected from a sample is measured as a function of incidence angle. The layered growth is indicated by the existence of many superlattice peaks, which are due to the Bragg reflection by the superlattice planes. The spacing of these peaks is related to the thickness of the layers, whereas the amplitude is related to the admixture of one constituent into the other, the interfacial roughness, and the amount of strain present. See also: Electron microscope; X-ray diffraction

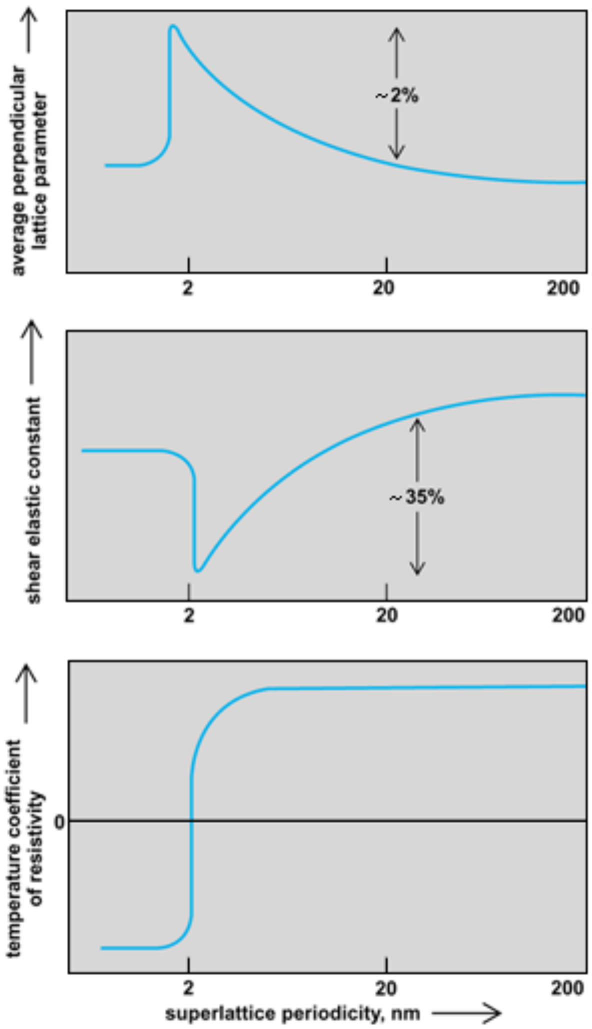

Fig. 2 Average perpendicular lattice parameter, shear elastic constant, and temperature coefficient of resistivity versus superlattice periodicity. (*After M. R. Khan et al.*, *Structural*, *elastic and transport anomalies in molybdenum-nickel superlattices*, *Phys*. *Rev*., *B27:7186–7193*, *1983*)

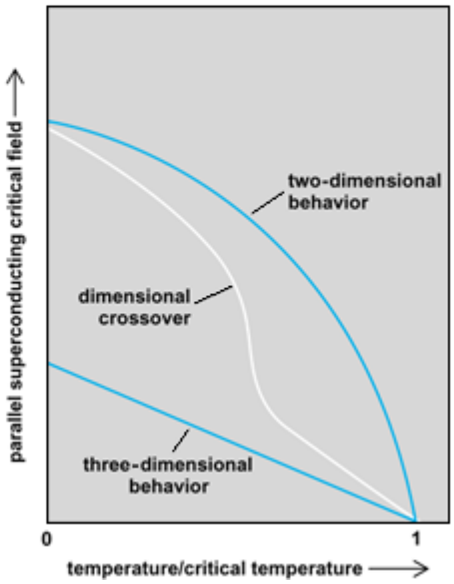

Fig. 3 Parallel superconducting critical field versus temperature at various layer thicknesses. (*After S. T. Ruggiero*, *T. W. Barbee*, and *M. R. Beasley*, *Superconductivity in quasi-two-dimensional layered deposits*, *Phys. Rev.Lett., 45:1299–1302, 1980*)

Physical properties

The normal-state properties of non-lattice-matched metallic superlattices show anomalies at small thicknesses of the order of 2.0 nanometers periodicity (that is, repeat distance; **Fig.~2**). The lattice expands slightly (approximately 2%) in the direction perpendicular to the layers, the shear elastic constant decreases markedly (approximately 35%), and the temperature coefficient of resistivity changes sign, as in a metal–nonmetal transition.

Artificially layered structures that are superconducting exhibit dimensional crossover, as is shown (**Fig. 3**) beautifully by the temperature dependence of the superconducting critical field. When the superconducting layers are thin and well separated, the critical field shows a characteristic square-root-like behavior, as is expected for two-dimensional superconductors. If the superconducting layers are close together, the layers are strongly coupled and show a linear temperature dependence typical of a three-dimensional material. At intermediate separation the behavior can change from three-dimensional at high temperatures to two-dimensional at low temperatures, a phenomenon known as dimensional crossover. Since the high-temperature ceramic superconductors are also layered, many of their properties are similar to those of artificially layered superconductors. See also: Superconductivity

Because of a short-range coupling mechanism that is not yet understood, the ferromagnetic layers in ferromagnetic-normal superlattices order with antiparallel (antiferromagnetic) alignment. As a consequence, the resistivity can exhibit changes as large as 150% with applied field (giant magnetoresistance). This amount is much larger than the ordinarily observed magnetoresistance of 2–3% in magnetic materials. In some cases a variety of magnetic coupling mechanisms have been observed across nonmagnetic layers, giving rise to new magnetic structures (in dysprosium-yttrium superlattices, for instance) and collective spin waves in molybdenum-nickel superlattices. See also: Magnetoresistance; Magnon

Applications

Artificially layered structures are especially useful for the construction of mirrors for soft x-rays since there are no suitable, naturally occurring crystals for this purpose. This application was one of the main motivations for research on artificially layered structures. Mirrors and polarizers for neutrons have also been manufactured and are currently used in the United States and Europe. Superlattices with zero temperature coefficient of resistivity are useful as resistor material, and high-critical-field-magnet tapes using superconducting-insulator superlattices have been proposed. Magnetic superlattices that exhibit giant magnetoresistance are incorporated into magnetoresistive recording heads. See also: Electrical insulation; Neutron optics; X-rays

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Bibliography

- M. Bartusiak, Architects in the laboratory, *Discover*, 2:60–61, 1981
- P. Dhez and C. Weisbuch (eds.), *Physics, Fabrication and Applications of Multilayered Structures*, 1988
- J. D. Dow and I. K. Schuller (eds.), *Interfaces, Superlattices and Thin Films,* 1987
- S. Maekawa, et al. (eds.), *Metallic Multilayers*, 1993
- I. K. Schuller, E. E. Fullerton, and Y. Bruynseraede, Quantitative x-ray diffraction from superlattices, *Mater. Res. Soc. Bull.*, 12(12): 33–38, 1992

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