SPECIAL ISSUE:

OPTICS OF NANOSTRUCTURES

Man-made semiconductor nanostructures provide us with new ways to investigate condensed matter under conditions of reduced dimensionality and could revolutionize optoelectronic technology.

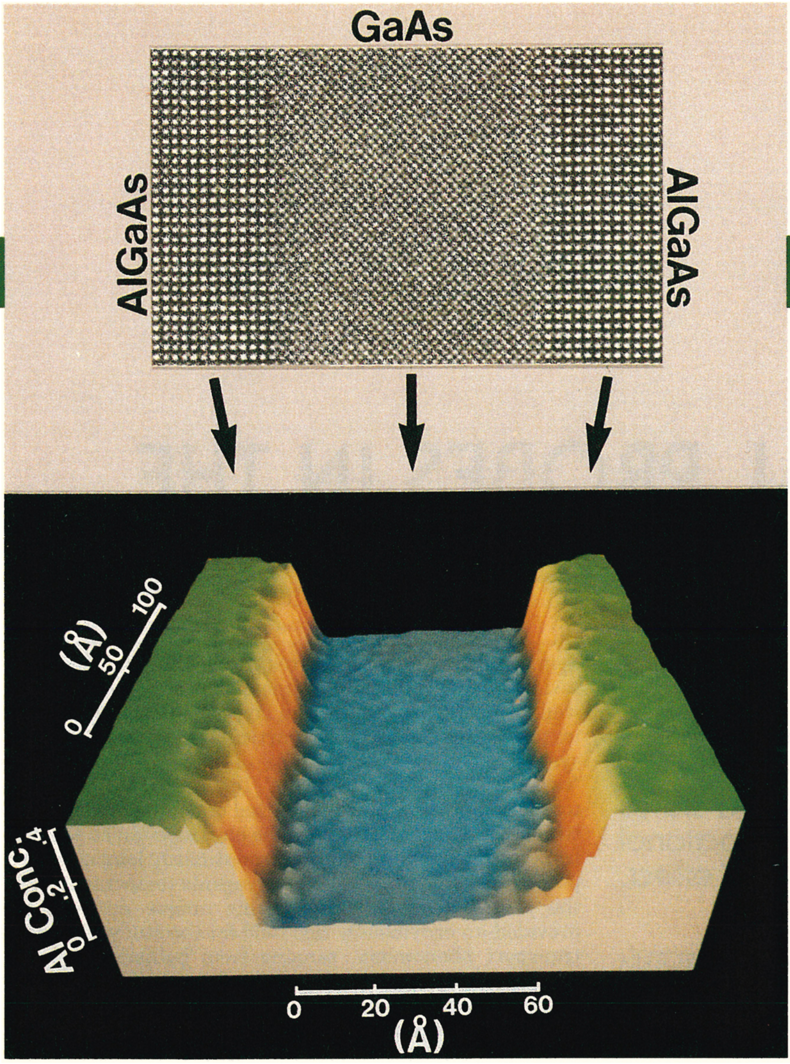
During the last decade semiconductor technology has continued to make impressive advances in miniaturization. It is now possible to fabricate artificial structures whose chemical compositions and shapes are controlled with a nanometer accuracy—comparable to interatomic distances. These man-made systems are too small to behave like the bulk parent compounds and too big to behave like atoms or molecules. We know from the basic principles of quantum mechanics that when the size of a system becomes comparable to the characteristic length scale that determines the coherence of the wavefunctions, quantum size effects occur. The properties then become size and shape dependent. The ability of modern technologies to actually make solid-state systems in which these conditions are realized opens new opportunities for investigation of condensed matter that has two, one or zero dimensions. Furthermore, because we can tailor some of the properties of these systems for specific purposes, nanostructures have the potential for revolutionary applications in electronics and optoelectronics. Feasibility demonstrations of some of these applications have already been performed, and implementations in actual devices have been achieved.

Modern techniques of crystal growth such as molecular-beam epitaxy and metal-organic chemical vapor deposition nowadays routinely produce ultrathin semiconductor layers, or quantum wells, that are smooth on an atomic scale. The figure at right shows an MBE-grown gallium arsenide quantum well, surrounded by aluminum gallium arsenide layers. The upper part of the figure shows an atomic-resolution micrograph of the structure. The chemical composition is encoded in this electron diffraction image: In the central, gallium arsenide layer, the dots actually represent rows of atoms. For this particular sample one can count 27 atomic rows of each species. This determines the thickness of the quantum well—approximately 60 Å. Since the sample area is of the order of several square centimeters, a number of its properties are almost two-dimensional. This is clarified by the three-dimensional plot in the lower part of the figure, which displays the variation across the structure of the composition, and hence of the energy gap between the conduction band and the valence band, at the center of the Brillouin zone. This plot helps the eye catch the atomic-scale roughness of the two interfaces. It also explains how the dimensionality of the elementary excitations is reduced. For example, when mobile carriers (electrons and holes) are introduced into the structure they find their way to the lowest energy states in their respective bands and therefore settle in the ultrathin central layer. The carriers behave as if the third dimension, perpendicular to the layer, did not exist!

One can further control the lateral dimensions of such structures by lithographic techniques, chemical adjustment of the crystal growth or application of a magnetic field. The artificial structures obtained by these methods have revealed a wealth of novel physical properties. Optical properties in particular are very sensitive to quantum confinement. When a photon is absorbed in a material, it creates an electron–hole pair, and the two particles interact strongly by electrostatics. In semiconductors, because the effective masses are small and the dielectric constant large, the exciton (bound state of the electron–hole pairs) is large on the atomic scale. Depending on the material, the corresponding Bohr radius a_0, which sets the natural length scale for all optical processes, is about 50 Å to 500 Å. One can observe massive changes in optical properties when the dimension of a semiconductor sample, in one or several directions, approaches a_0. The five articles of this special issue survey some of the most intriguing and unusual optical phenomena recently observed in semiconductor nanostructures.

Arto Nurmikko and Aron Pinczuk, in the article on page 24, describe how optical techniques are used to probe the states of two-dimensional electron gases at ultralow temperature and in magnetic fields. Because of the extraordinary mobility of two-dimensional electron gases, the electron mean free path can exceed several microns. The resulting many-electron correlation produces new states of matter, such as the integer and fractional quantum Hall condensates and (maybe) the still elusive Wigner crystal (see PHYSICS TODAY, December 1990, page 17). The quantum Hall effect was discovered and investigated by electron transport techniques. Recent experiments using inelastic light scattering have observed collective excitations of the incompressible quantum fluid associated with the fractional quantum Hall state.

Artificial superlattices can increase by several orders



GaAs quantum well structure. Top: Atomic-resolution micrograph reveals the chemical composition with atomic accuracy. Bottom: Three-dimensional plot of the aluminum concentration across the nanostructure. Over one or two atomic layers, the Al concentration varies from 0 in the central GaAs quantum well to 40% in the outer layers. (Courtesy of Abbas Ourmazd, AT&T Bell Labs.)

of magnitude the spatial wavelength of the periodic potential seen by electrons in a crystal. Thus they can facilitate the observation and investigation of some old concepts of quantum mechanics that had until recently evaded experiments. This is illustrated in the article on page 34 by Emilio Mendez and Gérald Bastard, who describe how superlattices have permitted the observation of the Wannier–Stark ladder and brought us closer to the realization of the Bloch oscillator.

In my article, on page 46, I review the nonlinear optical properties and dynamics of low-dimensionality materials when they are excited and probed by intense or ultrashort light pulses. The quantum confinement of electron–hole pairs involved in interband transitions enhances the optical response and strengthens the many-body collective effects. This results in an interaction with ultrashort pulses of light that is qualitatively different from that involving independent atoms. Surprisingly, the physics governing this interaction has profound similarities with that of superconductors close to the superconducting transition.

In the article on page 56, Detlef Heitmann and Jörg Kotthaus give an update of progress toward the realization of quasi-one-dimensional quantum wires and quasi-zero-dimensional quantum dots via electrostatic confinement in the plane of a two-dimensional electron gas. When, in addition, a magnetic field is applied, the motion of electrons becomes very sensitive to the relative strengths of the magnetic confinement (measured by the cyclotron radius) and of the electrostatic confinement, which determines the geometry of the quantum dots and wires. This very delicate balance gives rise to beautiful interference and coupling effects that are probed by far-infrared spectroscopy.

In the article on page 66, Yoshihisa Yamamoto and Richart Slusher survey how microcavities fundamentally modify the way semiconductor lasers operate by changing the modes of electromagnetic radiation that can interact with matter. Yamamoto and Slusher describe how it is possible now to control processes as fundamental as spontaneous emission and, more amazingly, how this ability can be exploited for application to novel optoelectronic devices.

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