Advanced Epitaxy for Future Electronics, Optics, and Quantum Physics: Seventh Lecture International Science Lecture Series

Arthur C. Gossard, University of California at Santa Barbara, Organized by the National Research Council and the Office of Naval Research

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SEVENTH LECTURE
INTERNATIONAL SCIENCE LECTURE SERIES

ADVANCED EPITAXY FOR FUTURE ELECTRONICS, OPTICS, AND QUANTUM PHYSICS

by

Arthur C. Gossard

Professor of Materials, Electrical, and Computer Engineering

University of California at Santa Barbara

NATIONAL ACADEMY PRESS

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Preface

The International Science Lecture Series (ISLS) was established in 1990 at the request of (then) Chief of Naval Research RADM J.R. Wilson, Jr., USN. The ISLS is a cooperative venture between the National Research Council (NRC) and the Office of Naval Research (ONR). The primary objectives of the series are to facilitate the exchange of basic research knowledge and to identify opportunities for cooperative research on a global scale. Specifically, the ISLS is chartered to (1) advance free and open communication within the international scientific community at the basic research level; (2) assist ONR and the nation in keeping abreast of international scientific research directions and results; and (3) serve as a mechanism through which collaborative research projects can be identified.

To achieve these objectives, distinguished lecturers are identified by a committee operating under the auspices of the National Academies in scientific areas of interest to the ONR, such as materials science, information science and technology, oceanography, atmospheric sciences, and remote sensing. The lecturers travel abroad to provide formal lectures to host nations and participate in both formal and informal discussions with senior scientific representatives (including government, industrial, and academic representatives) in the host countries. The countries in which the lectures are delivered are selected on the basis of consultations with the international scientific community, including science attachés in U.S. embassies and senior representatives of ONR and its International Field Office. In addition, opportunities for reciprocal visits and lectures, collaborative research projects, and similar activities are identified during these interactions. A monograph of the lecture published at the conclusion of each lecturer's tour serves as the public record of the tour.

Advanced Epitaxy for Future Electronics, Optics, and Quantum Physics, by Arthur C. Gossard, professor of materials, electrical, and computer engineering at the University of California, Santa Barbara, is the seventh lecture in the series. Previous lectures in the series were the following:

- *The Heard Island Experiment*, by Walter H. Munk, Secretary of the Navy Research Chair at the Scripps Institution of Oceanography, University of California at San Diego;
- *Fountainhead for New Technologies and New Science*, by Rustum Roy, Evan Pugh Professor of Solid State Physics and professor of geochemistry at Pennsylvania State University;

- *Computing, Communication, and the Information Age*, by John E. Hopcroft, Joseph C. Ford Professor of Computer Science at Cornell University;
- *Traffic Management for High-Speed Networks*, by H.T. Kung, Gordon McKay Professor of Electrical Engineering and Computer Science at Harvard University;
- *Implementation Challenges for High-Temperature Composites*, by Anthony G. Evans, Gordon McKay Professor of Materials Engineering at Harvard University; and
- *Aspects of Weather and Space Weather in the Earth's Upper Atmosphere: The Role of Internal Atmospheric Waves*, by Michael C. Kelley, professor of electrical engineering at Cornell University.

Dr. Gossard and the accompanying delegation from the United States visited the Korea Advanced Institute of Science and Technology, the Kwangju Institute of Science and Technology, and Seoul National University during late September and early October 1999. The lecture tour consisted of the lectures, roundtable discussions, and tours at each institution. Roundtable discussions focused on current research programs and potential areas for collaboration. The U.S. delegation included Professor Gossard; Dr. Ronald Taylor, Naval Studies Board, and Mr. Thomas Munns, National Materials Advisory Board, both from the National Academies; and Dr. Yoon-Soo Park, Office of Naval Research. The lecture was first presented on September 30 to the Korea Advanced Institute of Science and Technology (KAIST) at Taejon. The Optoelectronics Research Center (OERC) hosted the visit to KAIST. OERC is a Korea Science and Engineering Foundation (KOSEF)-sponsored center where the staff performs multidisciplinary research on optical information processing and optical communications. Prior to Dr. Gossard's lecture, there was a roundtable discussion on September 29 that included representatives from OERC, the Korean Research Institute of Standards and Science (KRISS), and the Electronics and Telecommunications Research Institute (ETRI). Also, the KAIST staff provided a tour of the OERC laboratory facilities for the visiting delegation.

Dr. Gossard presented his lecture next at the Kwangju Institute of Science and Technology (K-JIST) on October 1. The lecture was hosted by the Research Center for Ultrafast Fiber-Optic Networks (UFON), another KOSEF-sponsored facility for developing fundamental and core optoelectronic technologies required for an ultrafast optical network. Discussions centered on the potential for developing quantum dot structures with the uniformity required for laser applications. The subsequent roundtable discussion included representatives from the department of information and communications at K-JIST, the department of materials science and engineering at K-JIST, Honam University, and Mokpo National University. The visiting delegation also toured the laboratory facilities in the information and communications and materials science and engineering departments of K-JIST. After its session at K-JIST, the group met with the mayor of Kwangju, who described the city's efforts, under a plan entitled "Photonics 2010: Kwangju Creating Light," to become the center of the Korean photonics industry.

On October 4, Dr. Gossard made the third and final presentation of his lecture at Seoul National University (SNU) as part of the visit to the main Kwanak campus in Seoul. This part of the lecture tour was hosted by the Inter-University Semiconductor Research Center (ISRC). ISRC's purpose is to foster collaboration between universities and industries that are affiliated with the center, placing emphasis on fabrication (making and testing materials and devices rather than relying on modeling). At Seoul the roundtable discussion included representatives from the departments of physics, materials science and engineering, and electronics engineering at SNU, the Samsung Advanced Institute of Technology, and Sogang University.

The Naval Studies Board and the Office of Naval Research would like to thank their gracious hosts in Korea: Young-Se Kwon, director of OERC; Hyo-Gun Kim, president of K-JIST; Un-Chul Paek, chairman of the department of information communications, K-JIST; and Jong-Chun Woo, professor of physics and dean of the graduate school, SNU.

Abstract

The future development of electronics, optics, and, quite probably, quantum physics is being driven by advances in epitaxial materials. Band gap engineering, wafer bonding techniques, and epitaxial regrowth technology will push transistors far beyond the present speed barriers. Oxide growth within epitaxial layer structures and new advances in tunnel structures will push the development of the next generation of high-performance laser arrays and of efficient cascade laser designs. Perfection of the growth of semiconductor nitrides will move future electronics to higher powers and to suitability for extreme environments while revolutionizing lighting and display. Growth technologies to incorporate metallic particles and magnetic elements within high-quality semiconductors promise ultrafast electro-optical components for chemical and biological applications as well as electronically controlled magnetism for future memories and electrical/magnetic hybrid devices. Quantum dot materials will lead the field of signal electronics while hopefully providing a new proving and discovery ground for quantum physics. This paper will discuss the current progress in these areas.

Advanced Epitaxy for Future Electronics, Optics, and Quantum Physics

Rapid developments in semiconductor technology are occurring that are based on synthesis of thin layers and multilayered films of semiconductor crystals. These artificially layered materials can be grown in structures that confine and guide both light and electrons in special ways. They form microarchitectural materials of great precision and design flexibility. In this paper we describe the growth and the applications of these artificially structured epitaxial materials. We will examine the structures, how they are grown, and how they are being used for new light sources and high-speed electronics. We will then look at newly developed epitaxial structures, including quantum wires, quantum dots, and new materials for application to terahertz-frequency technology and nanometer-scale microelectromechanical systems.

The growth techniques that are the most widely used and most fully developed for making multilayered epitaxial (i.e., crystalline) films are molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD). Both techniques are capable of growing semiconductor films with thickness control and surface and interface smoothness with essentially atomic monolayer precision. In the case of MBE, crystals are formed by the delivery of neutral atoms in ultrahigh vacuum to the surface of the films [1]. The surfaces can be monitored during growth by electron diffraction so that surface smoothness and surface reconstruction are easily monitored. In MOCVD, gases react on a hot substrate to form the epitaxial films [2]. For both techniques, the smoothing of the surfaces can proceed at nearly an exponential rate. The smoothing is driven by a tendency of atoms to migrate on the surface and to stick at low spots, step edges, or depressions on the surface, where they can bind most strongly to the largest number of other atoms. The growth techniques were pioneered in the compound semiconductor families, especially the gallium arsenide III-V semiconductor family. Heteroepitaxy, in which a second material can be grown smoothly and without imperfection on an initial epitaxial film, was perfected initially in the GaAs/AlAs family and since then has been extended to many other systems. Differences in electron affinities between adjacent layers lead to a difference in potential energies for carriers in adjoining materials. This creates a potential step for both conduction electrons and holes. It is these potential steps in the conduction band and valence band edges that confine carriers and form the basis for band gap engineering [3]. The steps occur at the interfaces between the adjoining materials and can be very sharp. For an atomically abrupt interface, the potential steps are nearly atomically abrupt.

The potential wells formed by sandwiches of epitaxial semiconductor layers are illustrated in Figure 1. Quantization of the energy levels of the confined states of the electrons in the layers occurs as illustrated in the figure. Optical transitions between the confined electron energy states are allowed; consequently, electrons can emit photons as they drop from one energy level to another. Transitions from the lowest-conduction-band electron state to the highest-valence-band hole state produce the luminescence that is the basis of the light emission in quantum well lasers [4]. Today, quantum well lasers are the standard commercial semiconductor lasers and are used in applications as varied as fiber-optic communication; laser printing; materials processing; compact disc, CD-ROM, and digital video disc data storage; scientific instruments; optical pumping; medical treatment; and pointing and alignment. Recently developed quantum well lasers formed with gallium nitride epitaxy produce blue and white light previously impossible to produce with semiconductor devices. The greatly improved efficiency of semiconductor lasers and LEDs over traditional lightbulbs could revolutionize lighting [5]. Vertical-cavity, surface-emitting lasers (VCSELs) are a new generation of quantum well lasers that emit light from the surface of the epitaxial structures (as opposed to the edges). They can be formed into arrays of light emitters on a single chip with high efficiencies and low power usage.

In addition to enabling much of today's light wave technology, the flexible architecture and control of epitaxial growth are also powerful in allowing new, high-performance electronic devices and structures to be designed and fabricated. A particularly significant structure is the modulation-

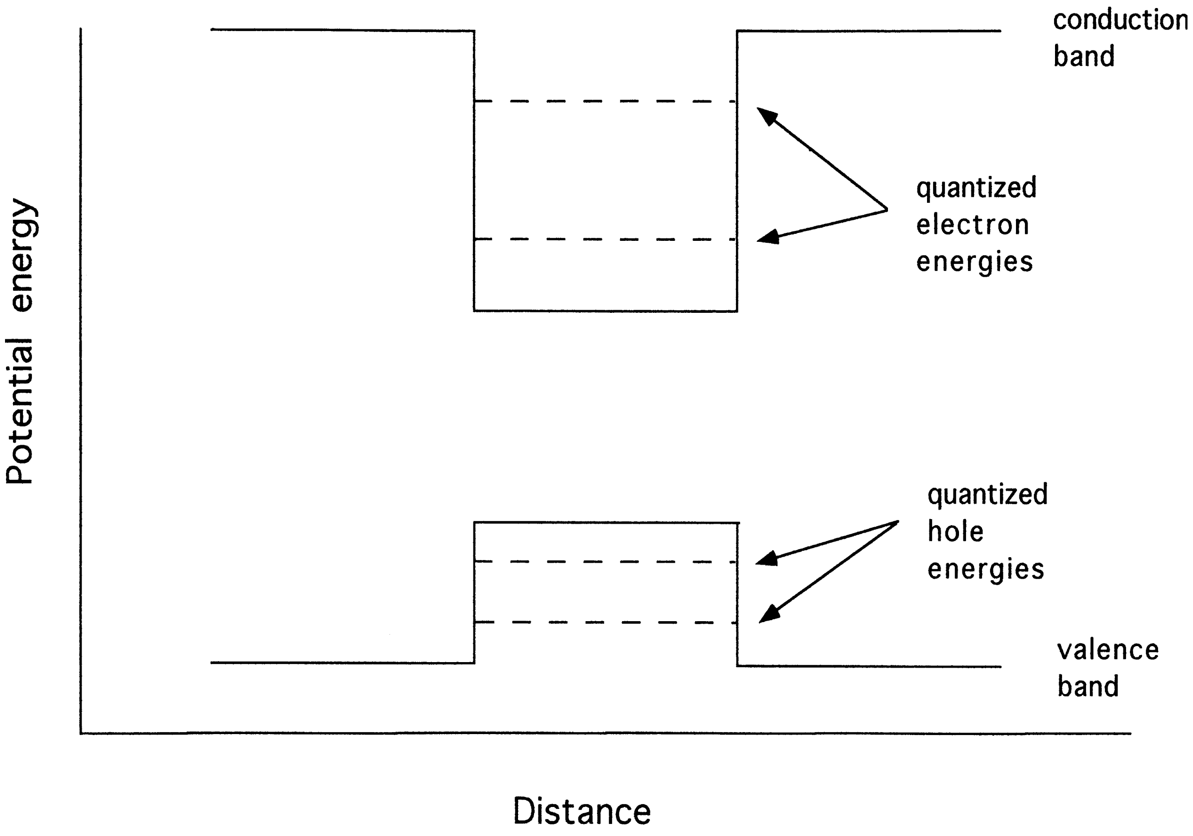

FIGURE 1 Potential wells for electrons and holes in epitaxial semiconductor sandwich. Wells are formed by layers of semiconductor materials with different electron affinities and band gaps. Lowest quantized electron energies and highest quantized hole energies are shown.

doped heterostructure. In this structure, also known as a selectively doped or high-electron-mobility heterostructure, electrons and holes move in thin undoped channel layers that are adjacent to, but separate from, layers containing the donor or acceptor impurity atoms that provide carriers to the highly conducting channel. The separation of charge carriers from the dopant impurities reduces the collisions of the carriers with the impurities and leads to enormously enhanced carrier mobilities. Record electron mobilities of more than 20 million cm^2/Vs have been achieved in these structures at low temperatures [6]. Although the electron mobilities are less at higher temperatures, where the electrons are scattered by lattice vibrations, the structures still provide major advantages in transistor design and performance. The modulation-doped, high-electron-mobility transistors are the most sensitive and efficient microwave and radio-frequency transistors. They have enabled increased operating frequencies and reduced receiver dish sizes in today's direct broadcast satellite systems. They are also in wide use in cellular telephones, where they provide greater sensitivity and reduced battery drain.

Modulation-doped heterostructures are also important in the study of the physics of electrons moving in two dimensions. The impact of modulation doping on the study of the physics of the two-dimensional electron gas derives from the relatively long time between carrier collisions in the high-mobility structures. This allows electrons to travel longer distances without collisions. Thus, in transverse magnetic fields, electrons can perform many orbital cyclotron revolutions before a scattering event. This allows clear observation of the quantization effects associated with cyclotron orbits and Landau levels (Figure 2). It makes possible an especially clear observation of the quantum Hall effect (in which the Hall resistance is quantized in units of h/e^2). It also allowed the discovery of the fractional quantization of the Hall effect (in which the Hall resistance is quantized in fractions of h/e^2) [7]. The fractional quantum Hall effect results from interactions among electrons at low temperatures in high magnetic fields, where all electrons in a two-dimensional electron gas lie in the lowest Landau level. The fractional states form an essentially new state of matter. The quantum Hall effect and the fractional quantum Hall effect were each the basis of a Nobel physics prize. Their chain of development illustrates an exceptionally fruitful interplay between device technology, advanced materials growth, and physics discovery.

With two-dimensional epitaxial structures having made strong impacts on devices and physics, it is natural to examine structures where the electrons are constrained to only one or zero degrees of freedom. One way to approach these lower-dimensional structures is by modification of a two-dimensional electron structure by surface gates or by etching. Small channels and confining regions can be formed so that the electron motion can be suitably constrained. Notable success has come from fabrication of small metallic electrical gates just above a selectively doped high-mobility, two-dimensional electron gas. In such gated structures, electrons can be guided through small constrictions (referred to as quantum point contacts) in which the electron conductance is quantized in integral multiples of e^2/h. The gates can also be arranged in shapes to create quantum dots in which electron motion in all directions is quantized (Figure 3). The quantized accumulation of charge within the dots can be observed in the so-called Coulomb blockade [8], and quantized motion of charge can be seen in the so-called quantum turnstile. An adiabatic quantum pump has recently been demonstrated in which electric current is produced by cyclic deformation of the confining potential of an open quantum dot [9].

As mentioned above, the formation of almost atomically smooth surfaces and interfaces in epitaxial growth is driven by the motion of adatoms on surfaces to stable incorporation sites. This provides a strong driving force for the formation of smooth surfaces. The lithographic processing of the surfaces that we have just discussed has been a powerful way to make quantum wires and quantum boxes (also known as quantum dots), but it is limited by size limits of lithography. Dimensions below

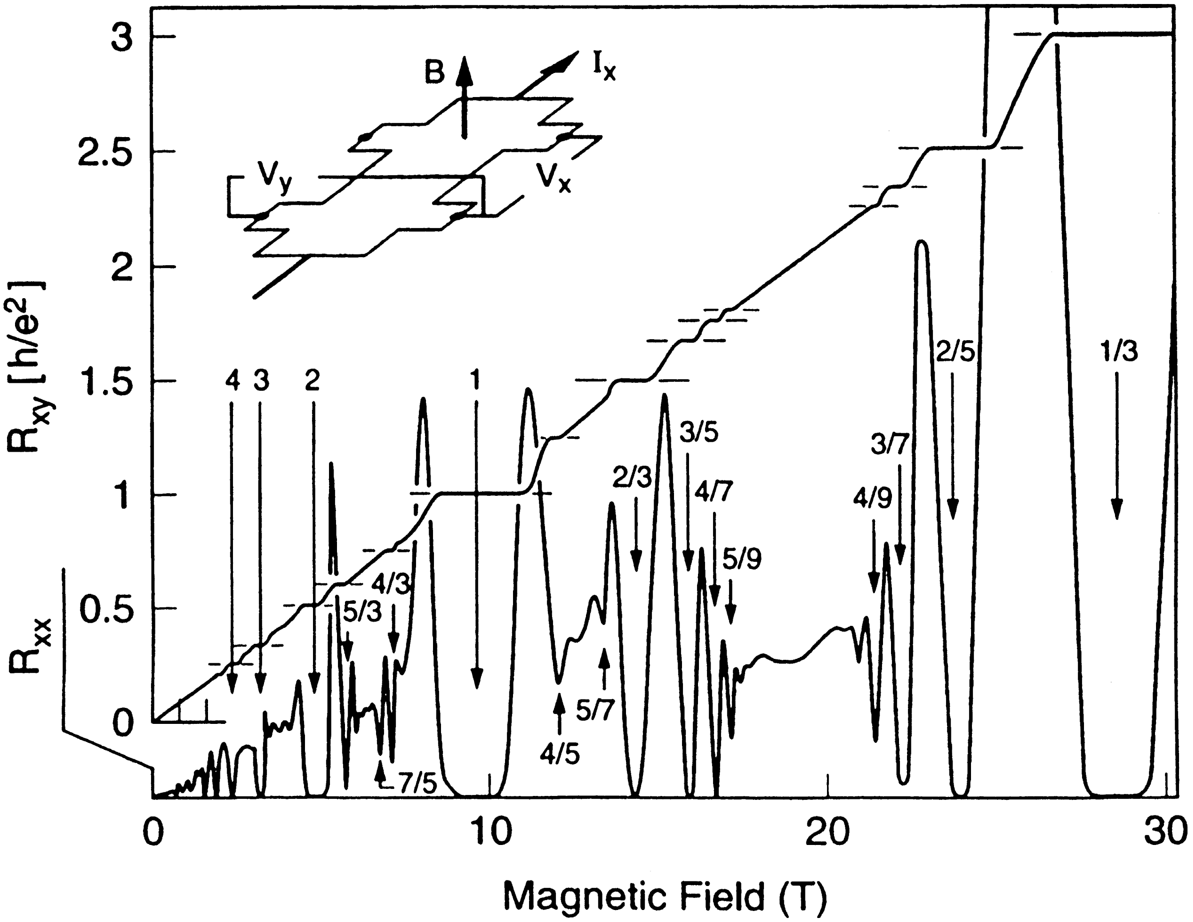

FIGURE 2 Quantum Hall effect and fractional quantum Hall effect in a two-dimensional electron gas in GaAs at T = 85 mK. The Hall resistance $R_{xy} = V_y/I_x$ and the magnetoresistance $R_{xx} = V_x/I_x$ are shown. Plateaus in R_{xy} and valleys in R_{xx} occur at integral and fractional values of the filling of the cyclotron (Landau) levels. Reprinted by permission from Stormer, H.L., D.C. Tsui, and A.C. Gossard. The fractional quantum Hall effect. *Reviews of Modern Physics*, Feb. 1999, vol. 71 (no. 2):S298-S305. Copyright 1999 by the American Physical Society.

0.1 micrometer become exceedingly difficult to achieve and control with lithographic processing. This makes it desirable to look for ways to produce spontaneous formation of wires, boxes, or rods in the crystal growth process. By solution chemistry, very small spherical particles that are effectively quantum dots or quantum boxes can be formed. Means to make rodlike particles by similar solution chemistry techniques are now being discovered [10].

In semiconductor epitaxy, growth techniques are also being developed to produce self-organized quantum dot and quantum wire structures. As an example of lateral self-organized growth of quantum structures, growth on an atomically stepped or terraced crystal surface provides a means of defining lines of atoms. The terraced surfaces can be produced by cutting a substrate wafer from a bulk crystal at a slight angle relative to the principal crystal axes of the bulk crystal. Epitaxial growth on such a surface typically proceeds by migration of the adatoms across the crystal terraces to incorporate at the step edges that occur between the terraces. Deposition of a submonolayer coverage of adatoms then produces atom-thick stripes of material that are distributed over the terrace edges. Alternately depositing different materials where the total coverage of each pair of depositions is an integral multiple or fraction of a monolayer then leads to a coherent alignment of the stripes in successive

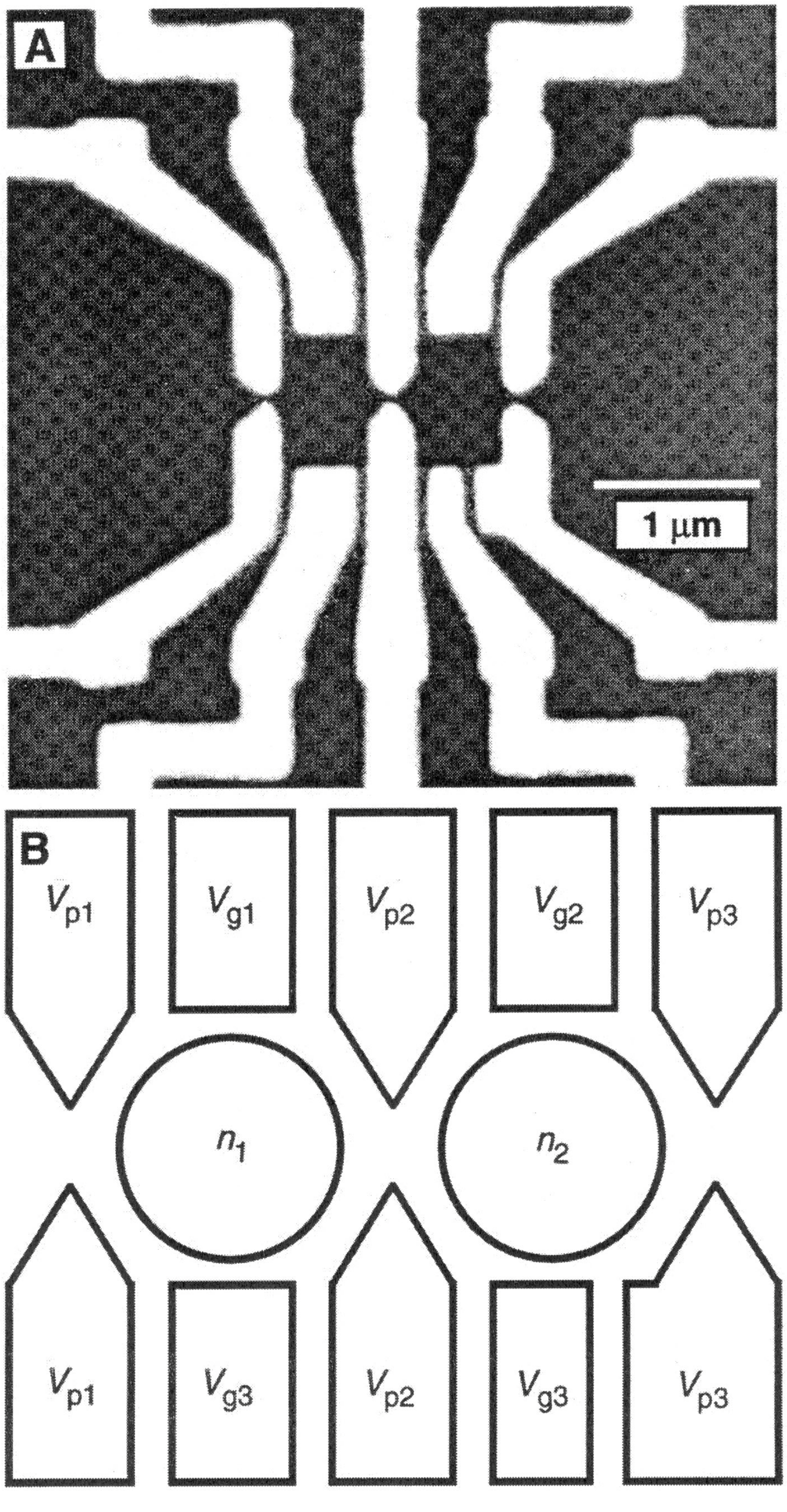

FIGURE 3 (A) Photograph by scanning electron microscope of coupled quantum dots formed by Cr-Au metal gates (light regions) on GaAs-AlGaAs two-dimensional electron gas. (B) Diagram of gates and coupled quantum dots. V_{g1} are gate electrodes, V_{p1} are point contact electrodes, and n_1 are quantum dots. Reprinted with permission from Livermore, C., C.H. Crouch, R.M. Westervelt, K.L. Campman, and A.C. Gossard. The Coulomb blockade in coupled quantum dots. *Science*, 22 Nov. 1996, vol. 274 (no. 5291):1332-1335. Copyright 1996 by the American Association for the Advancement of Science.

layers. The resultant epitaxial structure is an array, or superlattice, of quantum wires [11]. The periodicity of the superlattice is determined by the spacing between the terrace steps. The limits on the perfection of the quantum wire superlattices are the nonuniformity of the terrace step spacing, kinks in the terrace steps, and possible interdiffusion during growth.

When epitaxial structures are grown in which a material with a somewhat different crystal lattice spacing is grown on an original material, another kind of self-ordering can occur that provides an effective way to make quantum dots. In this case, adatoms with larger radii than the substrate atoms can relieve their compressive strain by forming islands in which they can spread out. This layer/island growth mode (known as Stranski-Krastanow growth) enables InAs depositions on GaAs substrates to organize themselves into islands [12]. InAs has a lattice constant that is 7 percent larger than GaAs. The islands are quantum dots whose sizes can be just a few nanometers. This is far smaller than can yet be achieved by lithography. Furthermore, the islands can be embedded by an overgrowth process. Then the process can be repeated to make stacked layers of these self-assembled quantum dots. The self-assembled quantum dot islands can be grown by both MBE and MOCVD. They form the basis for a rich and active pursuit of the science and technology of quantum dots. The localization of charge that they produce within semiconductor lasers can be beneficial to laser operation. Quantum dot lasers have been made with these materials, and it is believed that quantum dot confinement may be playing a major role in the successful operation of blue gallium nitride lasers, which typically contain InGaN active layers [13]. Electrical charging of the dots, one electron at a time, can be observed. Quantum-confined luminescence from the quantum states of the dots can also be seen. The major limitations on the dot structures are nonuniformity in their shape, size, spacing, and arrangement. Each of these issues is critically dependent on growth technique and technology. The ultimate impact of quantum dots on science and technology will depend strongly on the resolution of these issues.

In addition to quantum structures in semiconductors, it is interesting and useful to form metal/semiconductor composite nanostructures. A path to such structures has been provided by low-temperature epitaxy of compound semiconductors. It was discovered that epitaxial growth of crystalline GaAs could be performed at lower than conventional growth temperatures, with the result that excess As could be incorporated in the growth [14]. GaAs can be grown epitaxially at temperatures down to 200 °C, compared to more conventional growth temperatures of 500 ºC to 700 ºC. With an appropriate excess flux of arsenic relative to gallium, 1 to 2 percent of excess arsenic (relative to exactly stoichiometric GaAs) can be incorporated with low temperature growth. The excess arsenic provides electron traps (deep impurity states that pin the Fermi level in the gap of the GaAs), producing high-resistivity material and rapid recombination of electrons and holes. Annealing the material leads to diffusion of the excess arsenic to form metallic arsenic nanoparticles with diameter approximately 10 nanometers. The composite GaAs-As semiconductor-metal material can be applied to growing nonconductive insulation layers for application in field effect transistors to isolate semi-insulating substrates from transistor channel layers. The deep trap states and the metal particles in low-temperature-grown GaAs also provide efficient trapping of photo-induced carriers and rapid recombination of photo-induced electrons and holes. They are attractive for making fast photodetectors and phototransistors, eliminating long-lived carriers that would slow response and add dark current [15].

A significant application of low-temperature-grown GaAs has been the production of fast photoconductive materials for use in generation of terahertz-frequency electromagnetic waves [16]. The low-temperature-grown GaAs is the active element in photoconductive structures that generate electromagnetic radiation at the difference frequency between laser pumping beams that are striking the material. These photomixers produce levels and coherence of far-infrared terahertz-frequency radiation that can be the basis of a semiconductor far-infrared terahertz technology. These radiation sources are needed in astrophysics for the sensitive heterodyne detection of radiation from gases involved in star and galaxy formation as well as for detection of radiation from gases in Earth's atmosphere. Photoconductive mixers based on the low-temperature-grown GaAs and pumped by semiconductor lasers are providing highly coherent tunable CW radiation at record power levels in the terahertz frequency regime. This is particularly significant because of the absence of other viable semiconductor technologies for sources in the terahertz frequency region. Sources employing metallic nanoparticle composites of erbium arsenide (ErAs) particles in GaAs are now also showing promising performance in this application (Figure 4) [17]. The ErAs particles are formed by MBE codeposition of Er with GaAs and provide an alternate and highly engineerable approach to metal/semiconductor composites and high-speed photoconductors.

Yet another important functionality being provided by advanced epitaxial growth is the creation of magnetic semiconductors [18]. By inclusion of a sufficient concentration of magnetic atoms within a semiconductor, it is possible to produce magnetically ordered semiconductors. Extensive work has been performed on magnetic II-VI compound semiconductors such as CdMnTe. More recently, magnetic semiconductor alloys of GaMnAs have been grown with ferromagnetic Curie temperatures above 100 K in materials containing about 5 percent manganese. This raises the interesting possibility of "spintronics" and quantum computation technologies, in which information is stored and transmitted in semiconductors both as charge and as spin.

Still another emerging application of epitaxial semiconductors is in microelectromechanical systems (MEMS) and the smaller nanoelectromechanical systems (NEMS). Thin epitaxial layers that are remarkably flexible can be grown and subsequently released from their substrates by selective etching. This allows the formation of flexible, nearly perfect crystalline layers for MEMS or NEMS application. Free-standing films forming compliant cantilevers of thickness less than 100 nanometers

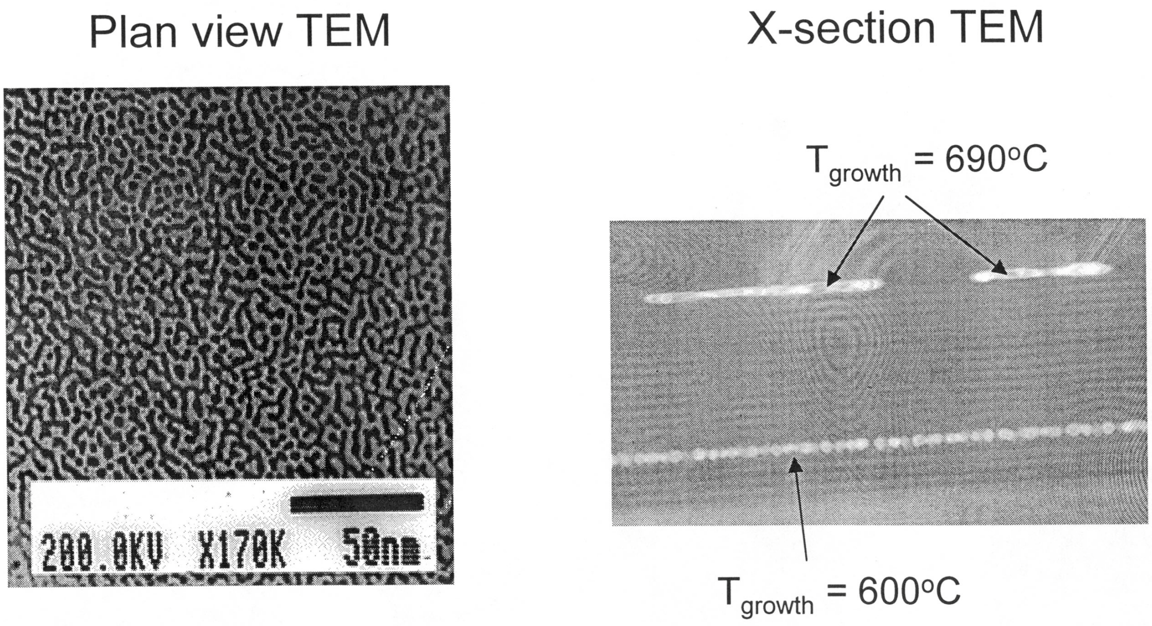

FIGURE 4 (left) Plan view transmission electron microscope (TEM) image of metallic ErAs islands in GaAs:ErAs semiconductor/metal epitaxial composite material. SOURCE: Kadow, C., J.A. Johnson, K. Kolstad, J.P. Ibbetson, and A.C. Gossard. Growth and microstructure of self-assembled ErAs islands in GaAs. *Journal of Vacuum Science and Technology B,* 2000, vol. 18 (no. 4):2199. (right) Cross-sectional TEM image of ErAs islands grown at T_{growth} = 690 °C and 600 °C. SOURCE: Schmidt, D.R., J.P. Ibbetson, D.E. Brehmer, D.J. Palmstrom, and S.J. Allen. Giant magnetoresistance of self-assembled ErAs islands in GaAs. *Materials Research Society Symposium Proceedings*, 1997, vol. 475:252.

have been fabricated. They provide sensitive elements for magnetic force magnetometry. The first measurements on these are showing sensitivities that are close to those of SQUID magnetometers [19].

When cantilevers are grown that contain modulation-doped, high-mobility electron layers near the surface, we have a way to incorporate field-effect transistors within the cantilevers. These field-effect transistors within the cantilever provide an ultrasensitive way to sense deflections of the cantilever. The cantilever deflections produce changes in electron density within the channel because of the strain-dependence of their electrical conductivity and because of piezoelectric effects that polarize the material when it is bent. When the surface of an appropriately oriented GaAs cantilever stretches, an electric field perpendicular to the surface develops. This field is produced by the piezoelectric effect and results from the relative motion of anions and cations with respect to each other in response to the strain. The field can accumulate or deplete electrons beneath a surface gate and thus turn on or off the field effect transistor. These self-sensing cantilevers show sensitivity comparable to the more conventional cantilever arrangements based on deflection of a laser beam reflected from the cantilever surface that are presently used in most atomic force microscopes [20]. But the self-sensing cantilevers offer considerably more potential for integration of arrays of cantilevers.

The structures and the applications that we have discussed here have given some idea of the development and uses of multilayered epitaxial thin films. In summary, the advanced epitaxial growth of semiconductor materials has repeatedly enabled interesting intersections between basic science and applied technology. The areas of science and technology that encompass new materials, new science, and new devices are enabled by the new epitaxial materials and give every indication of continued fruitfulness.

NOTES

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