CLAUDE WEISBUCH
BORGE VINTER

QUANTUM SEMICONDUCTOR STRUCTURES

Fundamentals and Applications

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Foreword

Once in a while a topic comes along that has universal appeal. It is both understandable to the undergraduate and challenging to the most sophisticated researcher, no matter what language he or she speaks. Such is the field of quantum semiconductor structures.

The fundamental, theory—that of a particle in a one-dimensional box—has been known since the earliest days of quantum mechanics. Even so, it is hard to believe that the field as we know it today was founded almost 20 years ago. At that time, groups at AT&T Bell Laboratories and IBM T. J. Watson Research Laboratories began studying very thin layers of GaAs and $Al_X Ga_{1-X}$ As heterostructures in which layers were less than 250Å in thickness; the first successful results were reported in 1973.

Both groups benefited greatly from early fundamental work in molecular beam epitaxy, although the materials, the physics, and the device engineering were quite distinct and separate fields. Devices, namely quantum well lasers, field effect transistors, and high-frequency oscillators, were proposed or actually discovered very early by the original research groups and have been evolving steadily ever since. Many basic discoveries—some readily understood by existing theory while others confounded the theories and required new models and concepts, have also been made. Although new and fascinating developments continue, the field is beginning to mature. The stage is set for a major publication to bring together the many elements of diverse achievement.

This book, with its encyclopaedic clarity, should be ranked with the best! When I read it for the first time, thoughts of Linus Pauling's *Nature of the Chemical Bond* and other great teaching/research texts passed through my mind. This book is of the "right stuff" and could achieve equivalent status in the years to come.

The wide range of achievement that is presented here with clarity, and liberally illustrated from the original literature, is all the more astonishing when one recalls that 15 years ago it was not possible to have a paper on this topic accepted in the mainstream conferences of the day. Now perhaps 50% of meetings on semiconductor and optoelectronic physics, materials, and devices are dominated by talks describing two-dimensional, one-dimensional, and zero-dimensional electronic systems in III–V semiconducting materials.

Dr. Claude Weisbuch is an excellent choice as the senior author of this book. His 20 years of experience in leading physics and semiconductor electronics research in major institutions on both sides of the Atlantic have developed the background required to speak with authority. Dr. Borge Vinter has added his own flavor, especially through theoretical derivations that are instructive and clear.

For those like myself, who have been waiting for a comprehensive exposé of this quantum semiconductor electronic field to be available, they need wait no longer—and they will not be disappointed. This book will be an authoritative reference for decades to come and will stimulate both newcomers and experienced researchers to greater achievement in this fascinating field.

Raymond Dingle
Sydney, Australia

Preface

This book is the outgrowth of a previous work published as an introductory chapter in *Applications of Multiquantum Wells, Selective Doping, and Superlattices* (Volume 24 of the series *Semiconductors and Semimetals*, R. K. Willardson and A. C. Beer series editors, R. Dingle volume editor). Due to both the demand for an introductory text for student use and rapid progress in the field, a new, expanded student edition was needed.

The teaching demand is, of course, dictated by the extraordinary successes of low-dimensionality semiconductor heterostructures, both in fundamental and applied fields. After a slow start in the Seventies, pioneered by Esaki and Tsu for the transport properties, and by Dingle for optical properties, the field got a sudden impulse at the end of the decade due to improved growth methods, and breakthroughs in fundamental science (the Quantum Hall effect by von Klitzing) and applications (modulation doping by Störmer and Dingle and high-quality injection quantum well lasers by Tsang). The situation in the mid-Eighties is well reviewed in the aforementioned volume, where outstanding fundamental properties and applications were described: high-yield optical properties, electron mobilities up to 2.10^6 cm^2 V^{-1} s^{-1}, the normal and "anomalous" Quantum Hall effect, new material pairs from strained-layer epitaxy, low-threshold quantum well lasers, ultrahigh speed microwave and digital integrated circuits, and electro-optical and nonlinear materials with unexpected efficiencies.

Since then, the rate of progress has not slowed down: on the fundamental side electron mobilities now reach 12.10^6 cm^2 V^{-1} s^{-1}, the anomalous Quantum Hall effect has even fractional numbers, and lower dimensionality electrical systems exhibit numerous new effects (quantum point resistance, electron focusing, ballistic motion up to 100 μm, nonlocal propagation etc.). In the applications side, we are witnessing the ubiquity of the quantum well laser, which wins on all performance segments (threshold, power, linewidth, temperature coefficient, etc.) with the recent advent of strained-active layers, vertical-emitting lasers, and phased-arrays; electro-optical processing arrays reach large IC size with more than 2000 active elements. Devices based on both horizontal and vertical transport still progress at a fast pace, in speed and integration level. Finally, quantized semiconductor structures are an industrial reality as millions of low noise transistors (mainly for direct-broadcast-satellite receivers) and quantum-well lasers (mainly for compact-disc players) are produced every month.

The aim of the present book is to provide a short introduction to this many fascinating applications of quantized semiconductor structures and convey some of the bewilderment that one should encounter at the extraordinary field, which developed in a decade, and the pace at which it still expands. These applications are based on a theoretical background, which should be acquired not only by those who intend to study fundamental properties of quantized systems but also by those who devote their efforts to inventing and fabricating devices with ever-increasing performance. The number of fundamental topics relevant to the general understanding of the field of quantized semiconductor structures is quite large, and some choice had to be made to keep the size of this introductory book within reasonable bounds: we selected only those calculations that we feel every student should go through once, and we give only sketchy descriptions of all other theories, referring to more specialized texts for details.

The material in this book comes from various interactions with many individuals. Claude Weisbuch wishes especially to thank R. Dingle, who introduced him to the field back in 1979 and has since been not just a colleague but a friend and a source of major inspiration as well. At Thomson, since 1983, E. Spitz has provided unrestricted support, both in the company and as a friend. H. Störmer was an especially close colleague and friend during the Bell Labs years. Bell Labs was an outstandingly welcoming institution; very fruitful collaborations occurred, principally with A. Gossard, W. Wiegmann, W. Tsang, A. Cho, J. Hegarty, A. Sturge, R. Miller, P. Petroff, C. Shank, R. Fork, B. Greene, A. Pinczuk, and V. Narayanamurti. At Thomson-CSF, both of us would like to thank J. P. Harrang, J. Nagle, N. Vodjdani, P. Bois, E. Costard, S. Delaître, T. Weil, F. Chevoir, E. Rosencher, and A. Tardella, who at various times and in various capacities provided a stimulating environment and useful discussions. During three years, an especially fruitful and friendly collaboration was established with M. J. Kelly and his colleagues at GEC. More recently, another excellent teaming with J. Kotthaus, J. Williamson, S. Beaumont, C. Sotomayor-Torres, P. Van Daele, R. Baets, F. Briones, C. Harmans, E. Böckenhoff and H. Benisty provided many important insights. Colleagues have kindly supplied us with preprints and photographs for which we are most thankful. Jane Ellis of Academic Press has been a most supportive editor. Brigitte Marchalot made the physical production of this new edition possible through her talent and cooperation.

Claude Weisbuch
Borge Vinter

Contents

CHAPTER I

Introduction

1. The Advent of Ultrathin, Well-Controlled Semiconductor Heterostructures

Although the search for ultrathin materials can be traced quite far back,[1,2] the motivation for their production went up sharply when new types of devices[3,4] were predicted, such as the Bloch oscillator. At the same time, the advent of a new growth technique, molecular beam epitaxy (MBE),[5-12] opened the way to the growth of semiconductors atomic layer upon atomic layer. In 1974 two basic experiments were carried out: Esaki and Chang reported the oscillatory behavior of the perpendicular differential conductance due to resonant electron tunneling across potential barriers,[13] and the optical measurements of Dingle[14] showed directly the quantization of energy levels in quantum wells, the well-known elementary example of quantization in quantum mechanics textbooks.[14a] Studies of ultrathin semiconductor layers have since then proliferated at an explosive rate.

Owing to progress in crystal availability and control, basic understanding of low-dimensional systems, and applicability of heterostructure concepts, the recent years have also seen the emergence of a wide family of structures and devices, which can be classified into four main (overlapping) families, as shown in Table I. At this point it seems worthwhile to emphasize the various structures that will be described or mentioned in this review, as their abundance can sometimes be confusing. They are depicted in Fig. 1 by means of their band diagrams. In many of these structures, we will be

TABLE I

THE FOUR MAIN FAMILIES OF DEVICES ORIGINATING FROM ULTRATHIN, WELL-CONTROLLED SEMICONDUCTOR HOMO- AND HETEROSTRUCTURES [a]

TWO-DIMENSIONAL SYSTEMS

SDHT-TEGFET-HEMT-MODFET
NIPI
Quantum Wells
Quantum Hall Devices

CHARGE TRANSFER SYSTEMS

SDHT-TEGFET-HEMT-MODFET
NIPI
Real SpaceTransfer Devices

ONE-DIMENSIONAL SYSTEMS

Tunneling Structures
Superlattices, NIPI } in perpendicular transport
Quantum-Well Wires

BANDGAP ENGINEERED STRUCTURES

all of the above plus non-quantized-motion structures:

Double-Heterostructure Lasers
Graded-Gap APD
Heterostructure Bipolar Transistors (graded base or not)
Separate Absorption- Multiplication APD
Staircase Solid State Photomultiplier

[a] Note that the same structures can belong to several of the families and that, using the term *bandgap engineering* in its most general description of engineered structures with desired properties obtained by a tailoring of the band structure, all of the structures can be considered "bandgap-engineered."

interested in *quasi-two-dimensional* properties; the free motion of the carriers occurs in only two directions perpendicular to the growth direction, the motion in the third direction z being restricted to a well-defined portion of space by momentum, energy, and wave-function quantizations. Compared to "classical" heterostructures like double-heterostructure (DH) lasers,[15,16] the "quasi-2D" term means that the z motion is defined by one or a few quantum numbers, which is only the case in ultrathin structures and/or at low enough temperatures. We use here the word *quasi* to mark the difference with *exact* 2D systems in which the wave function is exactly confined in a plane, with no extension outside of that plane. In the

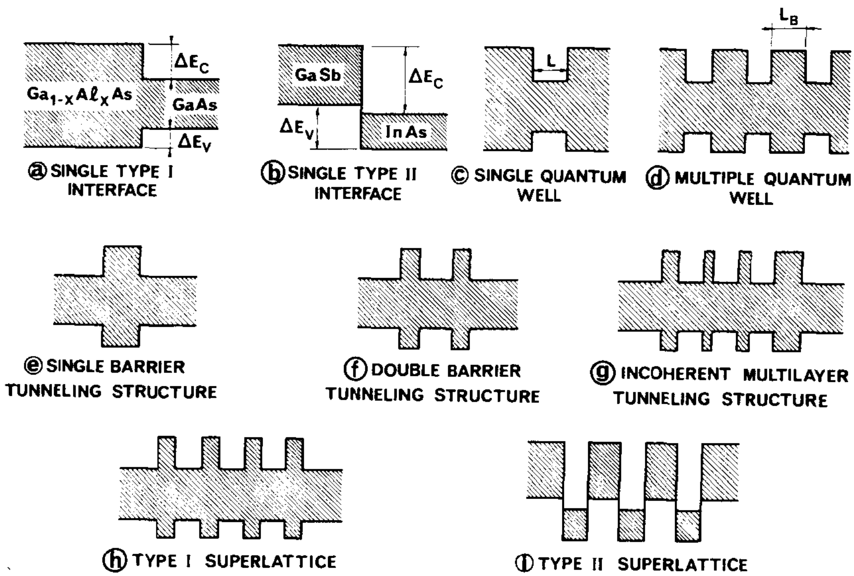

FIG. 1. The various types of heterostructures discussed or mentioned in this chapter. The widely used type-I heterostructure is shown in (a), with the band discontinuities such that both band edges of the smaller gap material are below those of the wide-bandgap material. In the type-II interface (b), the band structure is such that the top of the valence band of one of the compounds lies above the bottom of the conduction band of the other compound. Charge transfer occurs, leading to a conducting heterostructure. The type-I quantum well is shown in (c). The multiple-quantum-well structure [MQW, (d)] is such that L_B is large enough to prevent tunneling. Conversely, L_B in the single barrier (e), double barrier (f), type-I incoherent tunneling (g) and superlattice (h) structures is small enough to allow carrier tunneling across the barrier material. The difference between these two latter structures, (g) and (h), is that in the superlattice structure disorder and scattering are low enough to allow the *coherent* superlattice band states to build up, whereas in the incoherent tunneling structure scattering by disorder (here disordered interface fluctuations) destroys the phase coherence between the tunneling states. As charge transfer occurs in type-II multiple-quantum-well structures (i), these are considered as semimetallic superlattices, with the exception of ultrathin structures where energy quantization is so large that energy levels are raised enough in the respective bands to prevent any charge transfer.

rest of this chapter we shall refer to our quasi-2D systems merely as 2D systems.

The most widely known devices exploiting 2D motion are the quantum-well lasers[17,18] and the SDHT–TEGFET–HEMT–MODFET heterostructure transistors.[19–21] The parallel transport properties of $n-i-p-i$ structures[22] might prove useful in some devices like the heterojunction modulation superlattice. Due to the extraordinary properties of the quantum Hall effect,[23] some applications might be found in high-performance gyromagnetic devices. Quantum Hall structures are already being widely used as standard resistors in numerous national standards laboratories.

In some cases, we will be interested in the *one-dimensional* phenomena occurring along the z direction, either due to our search for perpendicular properties (i.e., perpendicular transport) or due to the unconfined extension of the wave functions in the z direction (superlattices or type-II multiple wells). Devices using these one-dimensional properties rely on tunneling or superlattice transport. Whereas tunneling devices such as the tunneling transistors[24] or negative differential resistance (NDR) tunneling diodes[25] have been demonstrated, clear superlattice effects have so far remained elusive. Great efforts are being devoted to the fabrication and understanding of true quantum one-dimensional systems best viewed as *quantum well wires*.[26,27]

The third family of devices shown in Table I relies on charge transfer, either *static* or *dynamic*. In the *static* case the charge transfer occurs between heterodoping and/or heterocomposition structures, leading to the appearance of electrostatic confining potentials due to depleted charges. Some of the 2D systems discussed above rely on this charge-transfer effect. *Dynamic* charge transfer occurs when electric-field-heated carriers can overcome potential barriers in heterostructures, leading to diminishing conductance and thus to NDR.[28-30]

Bandgap engineering[31] consists of the tailoring of an association of materials in order to custom design the structure for some desired properties unattainable in homostructures. A very good prototype of such structures is the double-heterostructure laser,[15,16] where one increases both the carrier confinement and optical wave confinement by using a heterostructure. It is clear that all the devices described above can be viewed as being due to bandgap-engineered structures. A number of other structures have been recently developed that do not involve space quantization in ultrasmall structures. These are shown in the lower part of Table I.

As can be seen in Table I, the variety of devices which have now been demonstrated is quite overwhelming, although the first devices (quantum-well lasers and modulation-doped structures) only appeared in the late 1970s.

The present book aims at presenting the basic physical phenomena encountered in these devices. The field is already so large, however, that we have concentrated on the basic phenomena encountered in the simplest and most widely used semiconductor pairs, the so-called type-I quantum wells and interfaces, where the small-bandgap material has both its electron and hole levels confined by the wider-bandgap materials. The other configurations (type-II quantum wells) have been thoroughly reviewed.[32-35] More details on strained-layer superlattices and their applications can be found in reviews of this young but rapidly developing field,[36–38] with applications in lasers[38] and infrared detectors.[39] The new field of amorphous semiconductors[40–43] is too far afield and will not be considered here, although many of the tools developed here can be applied to that subject. As new promising materials systems, not covered, one should point out SiGe/Si[44] and II-VI systems, the former for Si-compatible heterostructure and quantum devices (as evidenced by HBTs and quasi-direct gap optoelectronic material), the latter for optoelectronic material from middle infrared to blue and for new magnetic superlattice properties.

2. A Prerequisite: The Mastering of Semiconductor Purity and Interfaces

The mastery of layer growth is a prerequisite to all the structures which will be discussed in this book. We therefore wish to give an overview of the achievements in that field, referring the reader to more specialized texts for details. Quite different techniques have been used to grow quantized structures such as MBE,[5–12] metal-organic chemical vapor deposition (MOCVD),[45,46] hydride vapor transport,[47,48] hot-wall epitaxy[49] (HWE), or even liquid- phase epitaxy[50] (LPE). One can even trace through time how progress brought about by such a near-perfect growth technique as MBE has induced parallel spectacular progress in other growth techniques by demonstrating new and attainable goals.

The highly detailed control of crystal growth in MBE has been crucial to its progress and is due to the UHV environment, which allows for the implementation of powerful *in situ* analytical techniques. The growth sequence in an MBE chamber uses specific characterizations to ensure that each growth step is correctly carried out: before growth has started, mass analysis of residual molecules in the chamber detects any unwanted molecular species. Molecular beam intensities are precisely controlled by ion gauges. Substrate cleaning is checked by Auger electron spectrometry, which analyzes the chemical nature of the outer atomic layer. Reflection high-energy electron diffraction (RHEED) patterns monitor surface reconstruction after ion cleaning, annealing, and also during atomic layer growth. Studies of atomic layer growth through desorption measurements and RHEED analysis have provided a detailed understanding of MBE growth mechanisms.[51–54] RHEED oscillations due to recurrent atomic patterns in the layer-after-layer growth mode provide a very useful means of measuring layer thickness and are being more and more widely used.[55,56] TEM measurements of grown films have evidenced the smoothing effect of MBE growth on the starting substrate's roughness[57] (Fig. 2).

Although the growth kinetics of the MOCVD process is not as well monitored as that of MBE, recent progress leads to believe that MOCVD

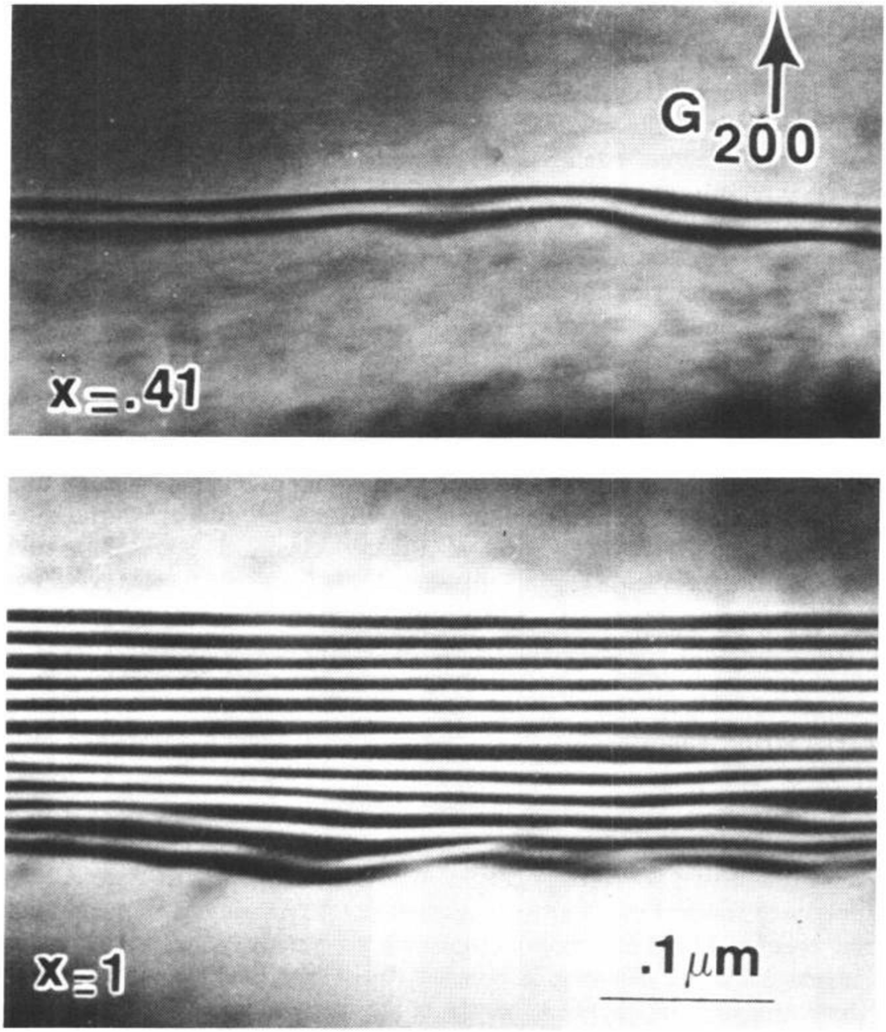

FIG. 2. Smoothing action of MBE quantum-well growth on interface roughness as observed in a dark-field transmission electron micrograph. The roughness of the starting GaAs surface is smoothed out by the growth of 3 to 5 quantum wells (courtesy of P.M. Petroff, AT&T Bell Laboratories).

growth leads to similar control of impurity content and interface abruptness[58–61a] (Fig. 3).

A vast amount of effort has also been devoted to characterization of interfaces, using various *ex situ* techniques such as chemical etching,[62] beveling,[62] SIMS,[63] Auger,[64] TEM,[65] and x rays.[66,67] The latter two tech-

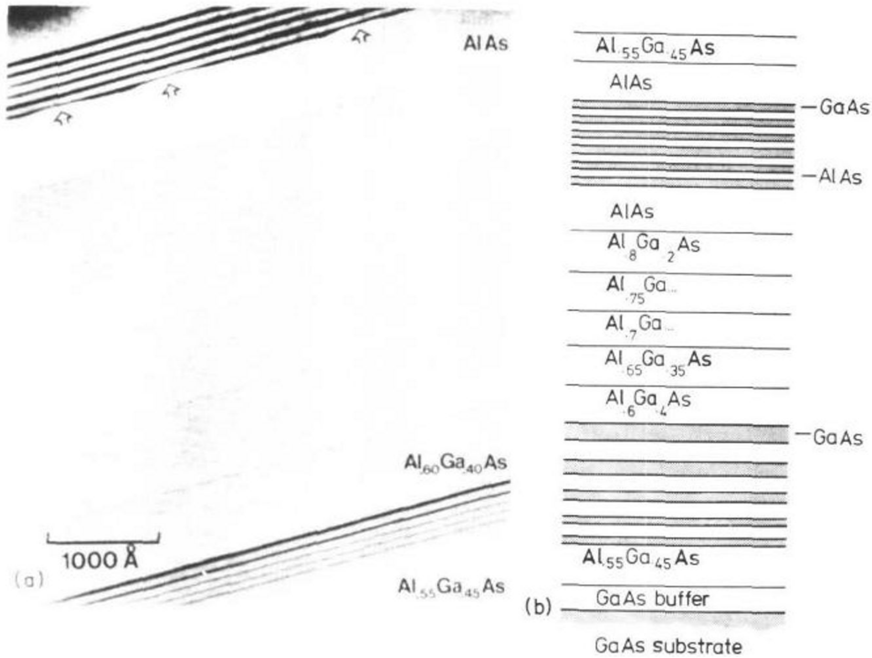

FIG. 3. (a) TEM characterization of a test sample grown by MOCVD. The growth sequence and the structure are shown in (b). The remarkable features are the sharpness of the very narrow GaAs layers (minimum ≈ 25 Å) appearing at the lower right-hand side corner, the interface roughness showing up at the uppermost interface of the AlAs layer, and the subsequent smoothing of this roughness by the multilayer growth (upper left-hand side corner) (after Leys *et al.*[61]).

niques have been shown to yield extremely precise information on a microscopic scale (Fig. 4). It has been thus shown that the preferred growth techniques, MBE and MOCVD, which are far from equilibrium growth processes, allow very low growth rates and thus good control for desired abrupt changes. Hot-wall epitaxy, an evaporation method, also leads to good interface control but has been used much less, due to the required high-purity bulk material. VPE and LPE are near-equilibrium methods with large growth rates and instabilities in the regime where redissolution (LPE) or etching (chlorine VPE) could diminish the total deposition rate. Stringfellow[68] also involved Cl absorption in the Cl-VPE method as a limitation to atomic in-plane motion and hindered coalescence of islands during atomic layer formation. Frijlink *et al.*[58] pointed out the strong reactivity of aluminum chloride with reactor material, forbidding growth of Al-containing structures with the Cl method.