INSTITUTE OF PHYSICS

PHYSICS AND APPLICATIONS OF SEMICONDUCTOR QUANTUM STRUCTURES

EDITED BY
T YAO
J-C WOO

IoP

British Library Cataloguing-in-Publication Data

A catalogue record for this book is available from the British Library.

ISBN 0 7503 0637 8

Library of Congress Cataloging-in-Publication Data are available

Commissioning Editor: Tom Spicer
Production Editor: Simon Laurenson
Production Control: Sarah Plenty
Cover Design: Victoria Le Billon
Marketing Executive: Colin Fenton

Published by Institute of Physics Publishing, wholly owned by The Institute of Physics, London

Institute of Physics Publishing, Dirac House, Temple Back, Bristol BS1 6BE, UK

US Office: Institute of Physics Publishing, The Public Ledger Building, Suite 1035, 150 South Independence Mall West, Philadelphia, PA 19106, USA

Typeset in TEX using the IOP Bookmaker Macros
Printed in the UK by MPG Books Ltd, Bodmin

Preface

Since the revolutionary idea of 'artificial' semiconductor superlattice structures proposed by Esaki and Tsu in 1969, semiconductor quantum structures have opened up a new era not only in the research of physics and materials science, but also in the development of electronic and optical devices. In the initial stage of this field, study was limited to the two-dimensionally confined electron system, which led to the discovery of many novel phenomena such as quantum Hall effects, quantum confined Stark effects, Aharanov–Bohm effects. It is obvious that these discoveries are duc to advances in materials science, in particular the atomic-scale growth techniques such as molecular beam epitaxy and metal organic chemical vapour deposition. Well-known examples of application are quantum well lasers, high electron mobility transistors and resonant tunnelling diodes, which are based on the two-dimensional confinement of electrons.

In recent years, efforts in this field have been devoted to the fabrication and characterization of quantum structures with reduced dimensionality, namely one- and zero-dimensional structures, with remarkable advancement in material processing and micro-fabrication technology. The successful fabrication of quantum wire and quantum dot structures have enabled scientists to explore novel properties and new-concept devices. Some of the outstanding examples are Coulomb blockade effects, microcavity lasers, exciton-based nonlinear optical effects, and single-electron transistors.

In view of the rapid progress in this multidisciplinary area related to semiconductor quantum structures, the researchers in this field felt a need to hold a forum, where scientists in various backgrounds could get together to review recent achievements and to discuss the future directions of development. In order to fulfil such a demand, the 1998 Asian Science Seminar entitled the International Workshop on Physics and Application of Semiconductor Quantum Structures has been formed under the sponsorship of the Japan Society for the Promotion of Science (JSPS) and the Korea Science and Engineering Foundation (KOSEF).

In this workshop, experts and leading scientists were invited to cover the overall spectrum on the research activities in this field. This book is comprised of the invited lectures of this workshop and a number of reviews. This book starts with a perspective review on the evolution of semiconductor superlattices and quantum nanostrctures (part 1) followed by the fabrication and characterization of quantum structures (part 2), transport properties (part 3), optical properties (part 4), spin dependent properties (part 5), and device applications (part 6).

We would like to extend our sincere gratitude to the contributing authors of the articles, the organizing members of the workshop, and especially the sponsoring organizations of the workshop for their kind cooperation and support.

Takafumi Yao and Jong-Chun Woo
February 2000

Contents

Preface **xv**

PART 1
Plenary lecture **1**

1 The evolution of semiconductor superlattices and quantum nanostructures
L Esaki **3**
1.1 Introduction 3
1.2 Quantum structures 5
References 9

PART 2
Fabrication and characterization of quantum structures **11**

2 Formation and characterization of semiconductor nanostructures
J Motohisa and T Fukui **13**
2.1 Introduction 14
2.2 InGaAs quantum wires on GaAs multiatomic steps 15
2.2.1 Quantum nanostructures utilizing atomic steps 15
2.2.2 Formation of GaAs multiatomic steps on GaAs (001) vicinal surfaces 17
2.2.3 Fabrication of InGaAs quantum wire structures using multiatomic steps 20
2.2.4 Optical characterization of InGaAs quantum wires 24
2.2.5 InGaAs quantum wire lasers 28
2.3 GaAs and InAs quantum dots and related nanostructures by selective area growth 33
2.3.1 MOVPE selective area growth for quantum nanostructures 33
2.3.2 Selective area MOVPE of GaAs and InAs quantum dots on pyramidal structures 34

2.3.3 Fabrication and characterization of high-density quantum dot arrays and quantum dot network 39
2.3.4 Position controlled InAs quantum dots on GaAs pyramidal structures 44
2.3.5 Fabrication of single electron transistors and their transport properties 51
2.3.6 Resistance-load SET inverter circuit 55
2.4 Summary and outlook 58
Acknowledgments 60
References 61

3 New quantum wire and quantum dot structures by selective MBE on patterned high-index substrates
K H Ploog and R Nötzel **65**
3.1 Introduction 65
3.2 Results 66
3.2.1 Quantum wires on stripe-patterned GaAs(311)A 66
3.2.2 Dot-like structures on square- and triangular-patterned GaAs(311)A 67
3.2.3 Coupled wire-dot arrays on stripe-patterned GaAs(311)A 68
3.2.4 Uniform quantum dot arrays by hydrogen-enhanced step bunching on stripe-patterned GaAs(311)A 71
3.3 Concluding remarks 72
Acknowledgments 73
References 74

4 New fabrication techniques and optical properties of GaN and Si quantum dots
Y Aoyagi, S Tanaka and X Zhao **75**
4.1 Introduction 75
4.2 Formation of self-assembled GaN quantum dots using Si antisurfactant and optical properties of the dots 76
4.2.1 Experimental procedure 76
4.2.2 Experimental results 77
4.2.3 Discussion 80
4.3 Formation of nanocrystalline Si by Er doping and optical properties of the nanocrystal 81
4.3.1 Experimental procedure 82
4.3.2 Experimental results 82
4.4 Conclusion 86
References 86

5 Dislocation filtering techniques for MBE large mismatched heteroepitaxy
J M Zhou, Q Huang, H Chen and C S Peng **88**

5.1 Introduction 88
5.2 Survey of several dislocation filtering methods 89
5.2.1 Constant-composition layer 89
5.2.2 Strained-layer superlattices (SLS) 90
5.2.3 Composition graded layer 91
5.2.4 Patterned substrate 92
5.3 Low-temperature Si and/or GeSi buffer for GeSi alloy strain relaxation 92
5.4 New initial growth method for pure cubic GaN on GaAs (001) 97
5.5 InAs growth on GaAs using new prelayer technology 100
5.6 Conclusion 103
References 104

6 Growth of widegap II–VI quantum structures and their optical properties
T Yao **106**
6.1 Introduction 106
6.2 $ZnS/(ZnSe)_n/ZnS$ quantum dots 108
6.2.1 Fabrication of $ZnS/(ZnSe)_n/ZnS$ ultrathin quantum structures and their characterization 108
6.2.2 Temperature dependence of PL of ZnS/ZnSe quantum dot structures 114
6.2.3 Time resolved PL 118
6.2.4 The effect of substrate temperature on the formation of quantum structures 120
6.2.5 Mn doped ZnSe quantum dots 123
6.3 CdSe/ZnSe quantum dots 127
6.3.1 Alloying at the heterointerface 127
6.3.2 Self-organized formation of CdSe quantum dots 130
6.3.3 Spectral diffusion in CdSe QDs 132
6.4 Summary 135
Acknowledgments 135
References 136

PART 3
Transport properties in quantum structures **139**

7 Theory of quantum transport in mesoscopic systems: antidot lattices
T Ando, S Uryu, T Nakanishi and S Ishizaka **141**
7.1 Introduction 141
7.2 Antidot lattices 142
7.3 Commensurability peaks 144
7.4 Aharonov–Bohm-type oscillation 149
7.5 Triangular antidot lattices 153

7.6 Altshuler–Aronov–Spivak oscillation 156
7.7 Scattering matrix formalism 158
7.7.1 Quantum-wire junction 158
7.7.2 Energy bands and density of states 160
7.7.3 Commensurability peaks and Aharonov–Bohm oscillation 163
7.8 Anderson localization 166
7.8.1 Experiments 166
7.8.2 Thouless-number method 168
7.8.3 Numerical results 171
7.8.4 Localization oscillation 172
7.9 Summary and conclusion 174
Acknowledgments 175
References 175

8 Edge states in magnetic quantum structures and composite fermion systems
G Ihm, H-S Sim, K J Chang and S J Lee **178**
8.1 Introduction 178
8.2 Magnetic quantum dot 180
8.3 Composite fermions in an antidot: application of magnetic quantum dot 184
8.4 Composite fermion edge channels 188
8.5 Conclusion 191
Acknowledgments 192
References 192

9 Electronic states in circular and ellipsoidally deformed quantum dots
S Tarucha, D G Austing, S Sasaki, L P Kouwenhoven, S M Reimann, M Koskinen and M Manninen **194**
9.1 Introduction 195
9.2 Experimental details 196
9.3 Electronic properties of circular quantum dots 198
9.3.1 Atom-like properties: shell structure and Hund's first rule 198
9.3.2 Magnetic field dependence 199
9.3.3 Spin triplet for the four-electron ground state 201
9.4 Electronic properties of elliptical quantum dots 203
9.4.1 Deformed dots in rectangular mesa devices 203
9.4.2 Magnetic field dependence 206
9.4.3 Study of Zeeman effect on the spin states 207
9.5 Comparison to model calculations 209
9.6 Conclusions 213
Acknowledgments 213
References 214

PART 4
Optical properties **217**

10 Electron–hole and exciton systems in low dimensions
T Ogawa **219**
10.1 Introduction 219
10.2 Remarks on low-dimensional excitons 220
10.3 Single-exciton problem 221
10.3.1 One-photon absorption process 223
10.3.2 Two-photon absorption process 226
10.3.3 Dielectric confinement effect 228
10.4 A few exciton problems 230
10.4.1 An excitonic molecule in one dimension 230
10.4.2 Optical nonlinearity due to excitons 233
10.5 Excitonic many-body problems 237
10.5.1 Exciton Bose–Einstein condensation and density waves in one dimension 237
10.5.2 Optical responses of the Tomonaga–Luttinger liquid: the Mahan exciton 241
10.6 Conclusions and prospect 247
Acknowledgments 250
References 250

11 Size quantization and electron dynamics in nanometre-size semiconductors
T Goto **253**
11.1 Introduction 253
11.2 Two-dimensional size confinement in ultrathin PbI_2 nanocrystals 254
11.3 Size confinement of an exciton internal motion in ultrathin PbI_2 nanocrystals 258
11.4 Nonlinear optical processes in CuCl nanocrystals 259
11.5 Photoinduced phenomena in luminescence spectra of a single CdSe nanocrystal 267
References 271

12 Electronic properties of InAs/GaAs quantum dots
R Heitz, I Mukhametzhanov, O Stier, A Hoffmann, A Madhukar and D Bimberg **273**
12.1 Introduction 273
12.2 Experimental 275
12.3 Experimental results and discussion 277
12.3.1 Energy transfer processes 278
12.3.2 Temperature dependence 282
12.3.3 Local-equilibrium emission 286
12.3.4 Excited-state transitions 291

12.3.5 Phonon-assisted exciton recombination 293
12.4 Conclusions 296
Acknowledgments 297
References 297

13 Graded and coupled quantum wells for emission of radiation by intersubband emission
K D Maranowski, A C Gossard and K L Chapman **300**
13.1 Introduction 300
13.2 Review of intersubband emission 302
13.3 Emission from parabolic quantum wells 307
13.4 Optical excitation of parabolic quantum wells 313
13.5 Quantum interference effects 315
13.5.1 Absorption in coupled quantum wells 317
13.5.2 Interference of intersubband transitions 321
13.6 Conclusions 331
Acknowledgments 333
References 333

PART 5
Spin-dependent properties **335**

14 Spin-dependent properties of magnetic III–V semiconductors
H Ohno **337**
14.1 Introduction 337
14.2 Preparation and basic properties of (Ga,Mn)As 338
14.2.1 Molecular beam epitaxy 339
14.2.2 Lattice constant and local lattice configuration 339
14.3 Magnetic and magnetotransport properties 340
14.3.1 Magnetic properties 340
14.3.2 Magnetotransport properties 341
14.4 Origin of ferromagnetism 345
14.5 Heterostructures 347
14.5.1 Ferromagnetic/non-magnetic/ferromagnetic trilayers 347
14.5.2 Resonant tunnelling structures 351
14.6 Conclusion 352
Acknowledgments 352
References 352

15 Zeeman separation in GaAs quantum structures
J-C Woo and K-H Yoo **355**
15.1 Introduction 355
15.2 Zeeman effects of GaAs and $Al_xGa_{1-x}As$ bulk 356
15.3 $GaAs/Al_xGa_{1-x}As$ quantum well 357
15.4 $GaAs/Al_xGa_{1-x}As$ quantum dot and quantum wire 362

15.5 Concluding remarks 366
References 366

PART 6
Device applications **369**

16 Self-assembling of silicon quantum dots and its application to novel nanodevices
M Hirose **371**
16.1 Introduction 371
16.2 Self-assembling of silicon quantum dots 372
16.3 Quantum confinement in silicon dot 375
16.3.1 Valence band spectra and charging effect 375
16.3.2 Comparison with theory 379
16.4 Resonant tunnelling through a Si quantum dot 380
16.4.1 Device fabrication 380
16.4.2 Resonant tunnelling characteristics 381
16.5 Silicon quantum dot memory 382
16.5.1 Device fabrication 383
16.5.2 Memory characteristics of Si quantum dot floating gate MOS structures 383
16.6 Summary 385
Acknowledgment 385
References 385

17 Quantum devices based on III–V compound semiconductors
H Hasegawa, H Fujikura and H Okada **387**
17.1 Introduction 388
17.2 Brief general overview on compound semiconductor quantum devices 389
17.2.1 Wave-particle duality and devices 389
17.2.2 Quantum wave devices 389
17.2.3 Single electron devices 391
17.3 Formation of GaAs- and InP-based quantum structure by molecular beam epitaxy 395
17.3.1 Approaches for formation of quantum structures 395
17.3.2 Selective MBE growth of InGaAs quantum wires, dots and wire-dot coupled structures 396
17.4 Control of surfaces and interfaces of nanostructures 405
17.4.1 A key issue for nanofabrication 405
17.4.2 Formation technology of damage-free Schottky gates for quantum structures 406
17.5 Compound semiconductor quantum wave devices 413

17.5.1 Various lateral quantum wave devices investigated at RCIQE 413
17.5.2 Schottky IPG single and coupled quantum wire transistors 413
17.6 Compound semiconductor single electron devices 418
17.6.1 Key issues for SEDs and efforts at RCIQE 418
17.6.2 Voltage gain in GaAs-based lateral SETs having novel Schottky gates 420
17.6.3 Single slectron memory devices utilizing IPG quantum wire transistor and metal nanodots 425
17.7 Conclusion 429
Acknowledgments 429
References 429

18 Quantum interference in corrugated conducting wire transistors
K Park **433**
18.1 Issues and challenges in semiconductor nanostructures 433
18.2 Quantum transport; electron interference 436
18.3 Review on lateral quantum interference devices 438
18.4 Various characteristics of quantum interference devices 440
18.4.1 Uneven gate conducting wire 440
18.4.2 Electrostatic Aharonov–Bohm ring transistor 442
18.4.3 Electron diffraction transistor 446
18.4.4 One-dimensional corrugated quantum channel 448
18.5 Summary 449
Acknowledgments 450
References 450

19 Non-Markovian optical gain of strained-layer quantum-well lasers with many-body effects
D Ahn **452**
19.1 Introduction 452
19.2 The model 453
19.3 Numerical results and discussion 459
19.4 Conclusions 463
Acknowledgment 463
References 463

20 Generation of non-classical lights from semiconductor light emitters
M Yamanishi, H Sumitomo, M Kobayashi and Y Kadoya **465**
20.1 Introduction 465
20.2 Squeezing in photon-number fluctuations under constant-current operation 466
20.2.1 Basic physics for constant-current operation 466
20.2.2 Experimental arrangement and results (constant-current operation) 468

20.2.3 Pump-current-dependence of squeezing bandwidth 471
20.2.4 Framework of backward-pump model 471
20.2.5 Theoretical bandwidth for noise suppression in comparison with experimental results 474
20.3 Squeezing in photon-number fluctuations due to the backward pump process 476
20.3.1 Basic physics for constant-voltage operation 476
20.3.2 Experimental arrangements and results (constant-voltage operation) 477
20.3.3 New squeezing mechanism based on the backward pump process 480
20.4 Conclusions 482
References 483

PART 1

PLENARY LECTURE

Chapter 1

The evolution of semiconductor superlattices and quantum nanostructures

Leo Esaki
Tsukuba, Ibaraki 305-0047, Japan

In the early twentieth century, encounters with physical phenomena which require detailed analyses in nanoscale, such as electron motion, prompted the advent of quantum mechanics, since Newtonian mechanics could not possibly provide an adequate explanation for them. Electron tunnelling through nanoscale barriers is the most direct consequence of the law of quantum mechanics, for which the Esaki tunnel diode gave most convincing experimental evidence in 1957. Following the evolutionary path of quantum nanostructures, significant milestones are presented, including the birth of semiconductor superlattices, resonant tunnel diodes, quantum wires and dots.

1.1 Introduction

The twentieth century will be characterized by the fact that science and technology have made remarkable progress, including the establishment of quantum mechanics, the development of semiconductor devices with the invention of the transistor and the evolution of computers/telecommunications.

In the early century, encounters with physical phenomena such as the electron's motion or the photon's behaviour for which Newtonian mechanics could not possibly provide an adequate explanation, prompted the advent of quantum mechanics. The framework of quantum mechanics was established in the superb work of Werner Heisenberg, Erwin Schrödinger, Paul Dirac and Max Born in the period 1925–6.

During the infancy of the quantum theory, de Broglie [1] introduced a new fundamental hypothesis that matter was endowed with a dualistic nature—particles may also have the characteristics of waves. This hypothesis found expression, in the hands of Schrödinger [2], in the definite form now known as the Schrödinger wave equation, whereby an electron is assumed to be represented by a solution to this equation. The continuous non-zero nature of such solutions, even in classically forbidden regions of negative kinetic energy, implies an ability to penetrate such forbidden regions and a probability of tunnelling from one classically allowed region to another. The concept of tunnelling itself arises from this quantum-mechanical result, and has no analogy in classical mechanics. The subsequent experimental manifestations of that concept can be regarded as one of the early triumphs of the quantum theory. For instance, in 1928, Fowler and Nordheim [3] explained, on the basis of electron tunnelling, the main features of the phenomenon of electron emission from cold metals by high external electric fields, which had been unexplained since its observation by Lilienfeld in 1922.

In 1932, Wilson [4], Frenkel and Joffe [5], and Nordheim [6] applied quantum mechanical tunnelling to the interpretation of metal–semiconductor contact rectifiers such as those made from selenium or cuprous oxide. Apparently, this theory was accepted for a number of years until it was finally discarded after it was realized that it predicted rectification in the wrong direction for ordinary, practical diodes. It is now clear that, in the usual circumstances, the surface barriers met by semiconductors in contact with metals are far too thick to observe any tunnelling current.

In 1934, the development of the energy-band theory of solids prompted Zener [7] to propose interband tunnelling as an explanation for dielectric breakdown. He calculated the rate of transitions from a filled band to a next-higher unfilled band by the application of an electric field. In effect, he showed that an energy gap could be treated in the manner of a potential barrier. The Zener mechanism in dielectric breakdown, however, has never been proved to be important in reality. If a high electric field is applied to the bulk crystal of a dielectric or semiconductor, avalanche breakdown (electron–hole pair generation) generally precedes tunnelling, and thus the field never reaches a critical value for tunnelling.

With the invention of the transistor in 1947 came a renewed interest in the tunnelling process. Around 1950, the technology of Ge p–n junction diodes was developed, and efforts were made to understand the junction properties. In explaining the reverse-bias characteristic, McAfee *et al* [8] applied a modified Zener theory and asserted that low-voltage breakdown in Ge diodes resulted from interband tunnelling. Results of later studies, however, indicated that most Ge junctions broke down by avalanche, but by that time the name 'Zener diodes' had already been given to the low-breakdown Si diodes. Actually, Zener diodes are almost always avalanche diodes.

In these circumstances, in 1956, the investigation of interband tunnelling was initiated with heavily-doped Ge p–n junctions, where the junction width was successfully reduced to the range of nanometres.

We first obtained a backward diode which was more conductive in the reverse direction than in the forward direction. In this respect it agreed with