Oliver G. Schmidt
Editor

NANOSCIENCE AND TECHNOLOGY

Lateral Alignment of Epitaxial Quantum Dots

Springer

NANOSCIENCE AND TEC

Lateral Al

of Epitaxi

NanoScience and Technology

NanoScience and Technology

Series Editors:
P. Avouris B. Bhushan D. Bimberg K. von Klitzing H. Sakaki R. Wiesendanger

The series NanoScience and Technology is focused on the fascinating nano-world, mesoscopic physics, analysis with atomic resolution, nano and quantum-effect devices, nanomechanics and atomic-scale processes. All the basic aspects and technology-oriented developments in this emerging discipline are covered by comprehensive and timely books. The series constitutes a survey of the relevant special topics, which are presented by leading experts in the field. These books will appeal to researchers, engineers, and advanced students.

Applied Scanning Probe Methods I
Editors: B. Bhushan, H. Fuchs, and S. Hosaka

Nanostructures
Theory and Modeling
By C. Delerue and M. Lannoo

Nanoscale Characterisation of Ferroelectric Materials
Scanning Probe Microscopy Approach
Editors: M. Alexe and A. Gruverman

Magnetic Microscopy of Nanostructures
Editors: H. Hopster and H.P. Oepen

Silicon Quantum Integrated Circuits
Silicon-Germanium Heterostructure Devices: Basics and Realisations
By E. Kasper, D.J. Paul

The Physics of Nanotubes
Fundamentals of Theory, Optics and Transport Devices
Editors: S.V. Rotkin and S. Subramoney

Single Molecule Chemistry and Physics
An Introduction
By C. Wang, C. Bai

Atomic Force Microscopy, Scanning Nearfield Optical Microscopy and Nanoscratching
Application to Rough and Natural Surfaces
By G. Kaupp

Applied Scanning Probe Methods II
Scanning Probe Microscopy Techniques
Editors: B. Bhushan, H. Fuchs

Applied Scanning Probe Methods III
Characterization
Editors: B. Bhushan, H. Fuchs

Applied Scanning Probe Methods IV
Industrial Application
Editors: B. Bhushan, H. Fuchs

Nanocatalysis
Editors: U. Heiz, U. Landman

Roadmap of Scanning Probe Microscopy
Editors: S. Morita

Nanostructures – Fabrication and Analysis
Editor: H. Nejo

Applied Scanning Probe Methods V
Scanning Probe Microscopy Techniques
Editors: B. Bhushan, H. Fuchs, S. Kawata

Applied Scanning Probe Methods VI
Characterization
Editors: B. Bhushan, S. Kawata

Applied Scanning Probe Methods VII
Biomimetics and Industrial Applications
Editors: B. Bhushan, H. Fuchs

Fundamentals of Friction and Wear
Editors: E. Gnecco, E. Meyer

Oliver G. Schmidt

Lateral Alignment of Epitaxial Quantum Dots

With 446 Figures

Springer

Editor:

Prof. Dr. Oliver G. Schmidt
Prof. Dr. Oliver G. Schmidt
Institute for Integrative Nanosciences
IFW Dresden
Helmholtzstrasse 20
01069 Dresden, Germany
e-mail: o.schmidt@ifw-dresden.de

Series Editors:

Professor Dr. Phaedon Avouris
IBM Research Division
Nanometer Scale Science & Technology
Thomas J. Watson Research Center, P.O. Box 218
Yorktown Heights, NY 10598, USA

Professor Bharat Bhushan
Nanotribology Laboratory for Information
Storage and MEMS/NEMS (NLIM)
W 390 Scott Laboratory, 201 W. 19th Avenue
The Ohio State University, Columbus
Ohio 43210-1142, USA

Professor Dr. Dieter Bimberg
TU Berlin, Fakutät Mathematik,
Naturwissenschaften,
Institut für Festkörperphysik
Hardenbergstr. 36, 10623 Berlin, Germany

Professor Dr., Dres. h. c.
Klaus von Klitzing
Max-Planck-Institut für Festkörperforschung
Heisenbergstrasse 1, 70569 Stuttgart, Germany

Professor Hiroyuki Sakaki
University of Tokyo
Institute of Industrial Science,
4-6-1 Komaba, Meguro-ku, Tokyo 153-8505, Japan

Professor Dr. Roland Wiesendanger
Institut für Angewandte Physik
Universität Hamburg
Jungiusstrasse 11, 20355 Hamburg, Germany

ISBN 978-3-540-46935-3 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2007923281

Springer is a part of Springer Science+Business Media

springer.com

Typesetting: LE-TEX Jelonek, Schmidt & Vöckler GbR, Leipzig
Production: LE-TEX Jelonek, Schmidt & Vöckler GbR, Leipzig
Cover: eStudioCalamar S.L., F. Steinen-Bro, Pau/Girona, Spain

SPIN 11373360 57/3180/YL - 5 4 3 2 1 0 Printed on acid-free paper

Introduction

The unique success story of semiconductor physics and technology relies on the ability to highly integrate micro- and nanometer sized functional units on a single chip. Within the last years epitaxial quantum dots have become such functional units and moved to the forefront of cutting edge research to study the exciting physics of single quantum structures and to fathom their tremendous potential for device applications.

Quantum dots constitute a natural template to construct refined artificial matter, such as artificial atoms, molecules and possibly artificial crystals with entirely new electronic and optical properties. However, the full advantage of their unique properties can be exploited, only, if a controlled positioning or growth of the quantum dots inside a more complex device structure or a precise coupling between the quantum dots and a macroscopic periphery can be achieved. The prime task of this book is to review recent techniques, which allow the controlled positioning and lateral alignment of quantum dots on standard substrate surfaces.

The alignment techniques range from pure self-ordering mechanisms to advanced quantum dot growth on patterned substrates. In the former case, growth conditions, substrate orientations and layer sequences are optimized to achieve a high degree of lateral ordering. In the latter case, the nucleation centers of the quantum dots are defined by appropriate pre-patterning of the substrate surfaces. This approach allows for an absolute positioning of the quantum dots relative to marker structures, which are necessary to define a device at the position of the quantum dot in subsequent processing steps.

While this book clearly documents the great advance made in controlling the spatial position of quantum dots, there remain huge challenges that need rigorous tackling in future years. One of the biggest problems is the non-resonant energy spectrum of quantum dot ensembles, even if they are located in an apparently perfectly ordered array. The reason is that each quantum dot is slightly different in size, shape and composition and therefore emits a photon with a different energy. The question of “How identical are nanostructures and can we create identical nanostructures?” addresses many fields of today’s integrative nanotechnologies and is not inherent to quantum dots. For quantum dots, a solution might be a self-limiting growth mechanism or the manipulation of individual quantum dots after growth.

Part I of this book concentrates on the lateral self-alignment of epitaxial quantum dots. This self-alignment is realized by choosing appropriate growth conditions and special substrate surfaces. The self-alignment on a short range scale is exploited to create compact lateral quantum dot molecules. By stacking multiple quantum dot layers pronounced lateral ordering on a medium range scale is accomplished. The underlying growth mechanisms governing these phenomena are described and reviewed in detail in the first part of the book.

In the second Part the aim is to control the absolute lateral position of quantum dots on a long-range scale. Such long-range ordered quantum dot arrays might be useful for a high integration of single quantum dot devices, or to realize one, two, and three dimensional quantum dot crystals. Part II demonstrates that such artificial crystals can be created with high structural integrity and excellent optical quality. However, at the present stage the distances between quantum dots are too large as to observe new electronic band structures.

My gratitude goes to all authors having composed the 26 chapters of this book. It took more than two years to put together this work, but I am sure the effort was worthwhile and the book will serve as a helpful platform to understand the many fundamental questions of quantum dot growth as well as to further our efforts to eventually integrate single quantum dots on a single chip.

Oliver G. Schmidt

Contents

Part I Lateral Self-Alignment

I.1 General

1 Physical Mechanisms of Self-Organized Formation of Quantum Dots
V. Shchukin, D. Bimberg 5

2 Routes Toward Lateral Self-Organization of Quantum Dots: the Model System SiGe on Si(001)
C. Teichert, M.G. Lagally 49

I.2 Compact Lateral Quantum Dot Configurations

3 Short-Range Lateral Ordering of GeSi Quantum Dots Due to Elastic Interactions
J.A. Floro, R. Hull, J.L. Gray 79

4 Hierarchical Self-Assembly of Lateral Quantum-Dot Molecules Around Nanoholes
A. Rastelli, R. Songmuang, S. Kiravittaya, O.G. Schmidt 103

I.3 Ordering in Single Layers

5 Energetics and Kinetics of Self-Organized Structure Formation in Solution Growth – the SiGe/Si System
S.H. Christiansen, M. Schmidbauer, H. Wawra, R. Schneider, W. Neumann, H.P. Strunk 127

6 Ge Quantum Dot Self-Alignment on Vicinal Substrates
I. Berbezier, A. Ronda, A. Karmous 195

7 Lateral Arrangement of Ge Self-Assembled Quantum Dots on a Partially Relaxed Si_xGe_{1-x} Buffer Layer
H.-j. Kim, Y.-H. Xie, K.L. Wang 209

8 Ordering of Wires and Self-Assembled Dots on Vicinal Si and GaAs (110) Cleavage Planes
G. Abstreiter, D. Schuh 229

I.4 Ordering by Layer Stacking

9 Stacking and Ordering in Self-Organized Quantum Dot Multilayer Structures
G. Springholz, V. Holy 247

10 Self-Organized Anisotropic Strain Engineering for Lateral Quantum Dot Ordering
R. Nötzel 305

11 Towards Quantum Dot Crystals via Multilayer Stacking on Different Indexed Surfaces
Z.M. Wang, G.J. Salamo 325

Part II Forced Alignment

II.5 Growth on Shallow Modulated Surfaces

II.5.1 SiGe Islands

12 One-, Two-, and Three-Dimensionally Ordered GeSi Islands Grown on Prepatterned Si (001) Substrates
Z. Zhong, G. Bauer, O.G. Schmidt 353

13 Ordered SiGe Island Arrays: Long Range Material Distribution and Possible Device Applications
G.S. Kar, S. Kiravittaya, M. Stoffel, O.G. Schmidt 373

14 Nanoscale Lateral Control of Ge Quantum Dot Nucleation Sites on Si(001) Using Focused Ion Beam Implantation
A. Portavoce, R. Hull, F.M. Ross 397

15 Ge Nanodroplets Self-Assembly on Focused Ion Beam Patterned Substrates
I. Berbezier, A. Karmous, A. Ronda 429

16 Metallization and Oxidation Templating of Surfaces for Directed Island Assembly
O.D. Dubon, J.T. Robinson, K.M. Itoh 441

II.5.2 InGaAs/GaAs Quantum Dots

17 Site Control and Selective-Area Growth Techniques of InAs Quantum Dots with High Density and High Uniformity
K. Asakawa, S. Kohmoto, S. Ohkouchi, Y. Nakamura 463

18 In(Ga)As Quantum Dot Crystals on Patterned GaAs(001) Substrates
S. Kiravittaya, H. Heidemeyer, O.G. Schmidt 489

II.6 Growth on Surface Modulations of High Amplitude

II.6.1 SiGe Islands

19 Directed Arrangement of Ge Quantum Dots on Si Mesas by Selective Epitaxial Growth
K.L. Wang, H.-j. Kim 517

20 Directed Self-Assembly of Quantum Dots by Local-Chemical-Potential Control via Strain Engineering on Patterned Substrates
H. Wang, F. Liu, M. Lagally 525

21 Structural and Luminescence Properties of Ordered Ge Islands on Patterned Substrates
L. Vescan, T. Stoica, E. Sutter 543

22 Formation of Si and Ge Nanostructures at Given Positions by Using Surface Microscopy and Ultrathin SiO_2 Film Technology
M. Ichikawa, A. Shklyaev 569

II.6.2 III-V Quantum Dots

23 Pyramidal Quantum Dots Grown by Organometallic Chemical Vapor Deposition on Patterned Substrates
E. Kapon 591

24 Large-Scale Integration of Quantum Dot Devices on MBE-Based Quantum Wire Networks
H. Hasegawa, T. Sato, S. Kasai 639

25 GaAs and InGaAs Position-Controlled Quantum Dots Fabricated by Selective-Area Metalloorganic Vapor Phase Epitaxy
T. Fukui, J. Motohisa 665

26 Spatial InAs Quantum Dot Positioning in GaAs Microdisk and Posts
G.S. Solomon, Z. Xie 691

List of Contributors

Gerhard Abstreiter
Walter Schottky Institut
TU München, 85748 Garching
Germany

Kiyoshi Asakawa
TARA Center
University of Tsukuba
1-1-1, Ten-noudai
Tsukuba 305-8577, Japan

Günther Bauer
Institute for Semiconductor
and Solid State Physics
Johannes Kepler University
Altenbergerstr. 69, 4040 Linz
Austria

I. Berbezier
L2MP UMR CNRS 6137
Polytech'Marseille - Technopole
de Château Gombert
13451 Marseille Cedex 20,
France

Dieter Bimberg
Technische Universität Berlin
Institut für Festkörperphysik
Hardenbergstr. 36, 10623 Berlin
Germany

Silke H. Christiansen
Max-Planck-Institute
of Microstructure Physics
Weinberg 2, 06120 Halle/Saale
Germany

Oscar D. Dubon, Jr.
Department of Materials Science
and Engineering
University of California, Berkeley
CA 94720, USA

Jerrold A. Floro
Sandia National Laboratories
Surface and Interface
Sciences Department, Albuquerque
NM 87185-1415, USA

Takashi Fukui
Graduate School
of Information Science
and Technology, and Research
Center for Integrated Quantum
Electronics, Hokkaido University
N14, W9, Sapporo, 060-0814 Japan

Jennifer L. Gray
University of Virginia
Department of Materials Science
and Engineering
116 Engineers Way, Charlottesville
VA 22904-4745, USA

Hideki Hasegawa
Research Center for Integrated
Quantum Electronics (RCIQE)
and Graduate School
of Information Science
and Technology
Hokkaido University
N 13, W 8, Sapporo
060-8628, Japan

H. Heidemeyer
Max-Planck-Institut
für Festkörperforschung
Heisenbergstrasse 1, 70569 Stuttgart
Germany

V. Holy
Department of Electronic Structures
Faculty of Mathematics and Physics
Charles University
12116 Prague, Czech Republic

Robert Hull
University of Virginia
Department of Materials Science
and Engineering, 116 Engineers Way
Charlottesville, VA 22904, USA

Masakazu Ichikawa
Quantum-Phase Electronic Center
Department of Applied Physics
Graduate School of Engineering
The University of Tokyo
7-3-1 Hongo Bunkyo-ku
Tokyo 113-8656, Japan

Kohei M. Itoh
Keio University, 3-14-1 Hiyoshi
Kouhoku-Ku, Yokohama
223-8522, Japan

Eli Kapon
Ecole Polytechnique Fédérale
de Lausanne (EPFL),
Laboratory of Physics
of Nanostructures
Lausanne CH-1015, Switzerland

Gouri S. Kar
Max-Planck-Institut
für Festkörperforschung
Heisenbergstrasse 1, 70569 Stuttgart
Germany

A. Karmous
L2MP UMR CNRS 6137
Polytech'Marseille - Technopole
de Château Gombert
13451 Marseille Cedex 20
France

Seiya Kasai
Research Center for Integrated
Quantum Electronics (RCIQE)
and Graduate School
of Information Science
and Technology
Hokkaido University
N 13, W 8, Sapporo
060-8628, Japan

Hyung-jun Kim
Department of Electrical
Engineering
University of California Los Angeles
USA

Suwit Kiravittaya
Max-Planck-Institut
für Festkörperforschung
Heisenbergstrasse 1, 70569 Stuttgart
Germany

Shigeru Kohmoto
System Devices Research Labs
NEC Corporation
2-9-1 Seiran, Ohtsu
Shiga 520-0833, Japan

Max Lagally
Department of Materials Science
and Engineering
University of Wisconsin-Madison
1509 University Avenue, Madison
WI 53706, USA

Feng Liu
Department of Materials Science
and Engineering, University of Utah
Salt Lake City, UT 84112, USA

Junichi Motohisa
Graduate School
of Information Science
and Technology, and Research
Center for Integrated Quantum
Electronics, Hokkaido University
N14, W9, Sapporo, 060-0814 Japan

Yusui Nakamura
Department of Electrical
and Computer Engineering
Kumamoto University,
2-39-1, Kurokami
Kumamoto 300-2635, Japan

W. Neumann
Humboldt-University of Berlin
Institute of Physics
Newtonstraße 15
12489 Berlin, Germany

Richard Nötzel
eiTT/COBRA Inter-University
Research Institute
Eindhoven University of Technology
5600 MB Eindhoven
The Netherlands

Shunsuke Ohkouchi
Fundamental and Environmental
Research Laboratories
NEC Corporation
34, Miyukigaoka, Tsukuba
Ibaraki 305-8501, Japan

Alain Portavoce
University of Virginia
Department of Materials Science
and Engineering, 116 Engineers Way
Charlottesville, VA 22904, USA

Armando Rastelli
Max-Planck-Institut
für Festkörperforschung
Heisenbergstr. 1, 70569 Stuttgart
Germany

Jeremy T. Robinson
Department of Materials Science
and Engineering
University of California
Berkeley, CA 94720, USA

A. Ronda
L2MP UMR CNRS 6137
Polytech'Marseille - Technopole
de Château Gombert
13451 Marseille Cedex 20
France

Frances M. Ross
IBM Research Division
T.J. Watson Research Center
1101 Kitchawan Road,
Yorktown Heights, NY 10598, USA

Gregory J. Salamo
Department of Physics
University of Arkansas
Fayetteville, Arkansas 72701
USA

Taketomo Sato
Research Center for Integrated
Quantum Electronics (RCIQE)
and Graduate School
of Information Science
and Technology
Hokkaido University
N 13, W 8, Sapporo
060-8628, Japan

Oliver G. Schmidt
Max-Planck-Institut
für Festkörperforschung
Heisenbergstr. 1, 70569 Stuttgart
Germany

M. Schmidbauer
Institute of Crystal Growth
Max-Born-Straße 2
12489 Berlin, Germany