Preface

Let me start by defining the subject of this book, semiconductor nanostructures, using a strictly physical argument.

If the geometrical extent of a semiconductor, typically embedded in the matrix of another semiconductor, is reduced in one, two or three directions of space below the size of the "de Broglie wavelength" of a charge carrier—in other words, if it is reduced in size to only a few nanometers—it is a nanostructure. Reduction of dimensionality in one, two or three directions leads to quantum wells, wires or dots, respectively. The focus here is mainly on the ultimate limit, quantum dots.

The electronic—and to a lesser extent the vibronic—properties of low-dimensional structures (including their interactions such as electron–electron, electron–hole and electron–phonon interaction) depend qualitatively on the dimensionality of the structure and quantitatively on details of the geometry of the structure (its size and shape) and of the distribution of atoms inside. The electronic properties in turn control the linear and nonlinear optical and transport properties. Thus "geometrical architecture" opens enormous opportunities for designing completely novel materials or heterostructures. These opportunities extend far beyond the well-known "chemical architecture", where properties are modified by varying the chemical composition. Radically different from three-, two-, and one-dimensional structures in their electronic properties are zero-dimensional structures: quantum dots. Their "density of electronic states" is described by delta-functions and they show no dispersion of energy, thus resembling an atom in a dielectric matrix instead of a classical semiconductor. The Hamilton and momentum operators of quantum dots do not commute, leading again to novel physical properties. Figure 1 shows the variation of the density of states in structures of varying dimensionality.

The geometrical properties of quantum dots are controlled by the thermodynamic and kinetic parameters of the growth of strongly strained heterostructures, as long as we focus on the various fully epitaxial modes of their fabrication. Such

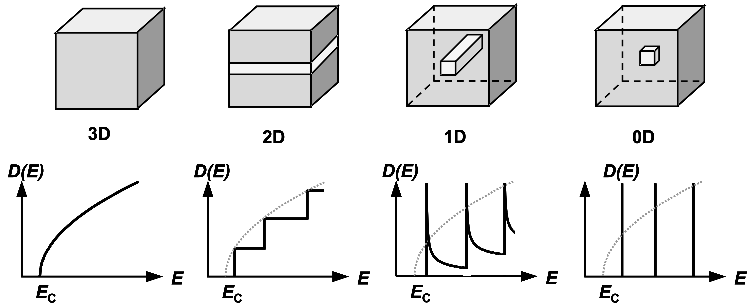

Fig. 1. Top: Schematic representations of three-, two-, one- and zero-dimensional heterostructures. Bottom: Densities of electronic states for the given case of dimensionality

growth modes lead to completely defect-free structures and interfaces. Fabrication of "classical" defect-free semiconductor heterostructures is based on the few existing lattice-matched or close to lattice-matched pseudomorphic structure families like GaAs/AlAs, or InP/InGaAsP. In contrast, quantum dot growth inverts this paradigm because a minimum difference of lattice constants is necessary to initiate self-organization effects, suddenly yielding an enormous wealth of "possible" combinations of material systems, complementary to the "classical" case.

Theoretical and experimental studies of growth mechanisms leading to the formation of nanostructures on different types of surfaces and for different semiconductors were one of the goals of the "Sonderforschungsbereich (SFB)" on "Growth Related Properties of Semiconductor Nanostructures", a "Center of Excellence", using a nonliteral translation, of the Deutsche Forschungsgemeinschaft (DFG), the German National Science Foundation. Self-ordering and self-organization effects play a decisive role for these newly discovered growth modes. Experimental investigations of nanostructures by structural, optical and transport methods, in addition to theoretical modeling of their electronic, linear and nonlinear optical properties were another objective. Novel experimental methods, like cathodoluminescence, cross-section tunneling microscopy, calorimetric absorption spectroscopy, near-field microscopy, to mention a few, had to be developed to meet the experimental challenges of gathering information on such ultra small structures. Discovery of many absolutely unique properties of nanostructures turned out to be of fundamental importance and present the starting point for a novel generation of photonic and electronic devices.

The reunification of Berlin brought together the members of this SFB, centered at the Technical University of Berlin. The principal scientists of the SFB came in almost equal numbers from some of the strongest research groups of the former West Berlin—the TU Berlin and the Fritz-Haber-Institute of the Max-Planck-Society—and from the former East-Berlin—the Humboldt University, the Paul-Drude-Institute and the Max-Born-Institute. In addition, guest scientists from all over the world contributed to its success, in particular those from the Ioffe Institute of the Russian Academy of Sciences.

The start of the SFB in the summer of 1994, after more than two years of preparation, was just in time. The international nano-wave then began to roll, triggered partly by the work of the SFB. After more than 12 years of operation, the papers published in 2006 by its researchers in international journals and at international conferences led them to the "top of the chart". The international citation index shows that many of the publications from the SFB belong to the most cited ones of the world in this area.

Three books [1–3] published in 1999, 2002 and 2004 summarize the initial worldwide fundamental work on quantum dots [1], aspects of epitaxial growth [2] and applications of quantum dots for novel nano-optoelectronics [3]. This new book summarizes what we believe represents the best, most important works on nanostructures of the last years, presented to the scientific community in a compact thus readable manner. Chapters 1–6 cover theoretical and experimental aspects of growth and structural studies. Chapters 7–10 are devoted to the theory of electronic and optical properties of quantum dots. Sections 11–16 finally focus on experimental studies of optical properties of nanostructures including ultra-high magnetic fields, ultra fast spectroscopy and emerging applications for novel nano-memories, quantum computing and cryptography. The authors of the contributions are the work package leaders of the SFB (Chaps. 1, 3–6, 8–10, 12, 13, 15 and 16) and of some of my coworkers (Chaps. 1, 2, 7, 11 and 14).

I thank my colleagues for the joy of working together for one and a half decades, lending me their support as a chairman of the SFB. I also thank the many reviewers for their constructive advice all along our way; the staff of the DFG for their never-ending patience and always-positive thinking; Claus Ascheron and the staff of Springer for their enthusiasm; Doreen Nitzsche for her energy reminding everybody to deliver and for completing the technical part of the book; and to my wife, Sigrun, for her patience when I looked overworked.

Berlin, March 2008 Dieter Bimberg

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