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Epitaxy of Nanostructures

With 192 Figures

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Preface

The general trend in modern solid state physics and technology is to make things smaller. The size of key elements in modern devices approaches the nanometer scale, for both vertical and lateral dimensions. Ultrathin layers, or quantum wells, had already gained broad acceptance for applications in micro- and optoelectronics by the 1980s. However, the development of heterostructures with lower dimensionality (quantum wires, where carriers are confined in two directions and move freely in one, and quantum dots, where carriers are confined in all three directions) took longer. It became clear that quantum wire and dot structures constitute the utmost technological challenge, whilst providing enormous advantages.

At the beginning of the 1990s, a few outstanding discoveries concerning self-organization phenomena at crystal surfaces for direct fabrication of nanostructures led to a change in the major paradigms of semiconductor physics and technology. This new approach in epitaxy enables fast parallel fabrication of large densities of quantum dots or wires for almost unlimited material combinations and has become the basis for a powerful new branch of nanotechnology. Quantum dots, coherent inclusions in a semiconductor matrix with zero-dimensional electronic properties persistent up to room temperature, have demonstrated fascinating physical properties and given birth to a novel generation of optoelectronic devices and systems.

The last decade of intense research into quantum dots by a great number of leading laboratories has clearly demonstrated that it is not sufficient to use the effects of self-organization alone when the aim is to achieve practical applications of funny objects. A profound understanding of the physics of nanostructure formation and the development of tools for controlling and tuning geometrical parameters and electronic spectra of the epitaxial systems is a prerequisite for any significant success in nanotechnology. To achieve this goal requires complementary studies including specially designed growth experiments, theoretical modeling of growth, and structural and optical characterization on a nanoscale. Combining effects generously provided by nature with further engineering of complex nanostructures allows significant progress in fabricating nanostructures suitable for devices. Many fundamental phenomena are now qualitatively understood, but no comprehensive survey on this subject exists in the literature. This book attempts to fill the gap.

Chapter 1 provides the motivation for entering the nanoworld, and discusses the fundamental paradigm changes in semiconductor physics. Chapter 2 describes the basic physics of molecular beam epitaxy used for the growth of semiconductor nanostructures, and gives an overview of structural and optical characterization techniques. Chapter 3 presents physical mechanisms governing the fundamental phenomena underlying the spontaneous formation of surface nanostructures, including periodically faceted surfaces and arrays of coherently strained islands. Chapter 4 expounds a large number of techniques and results in the engineering of nanostructures: improving uniformity in island size and spacing by stacking of dots, seeding of quantum dots allowing independent control of dot size and density, engineering exciton wavefunctions and control of photoluminescence polarization via stacking of dots, nanoengineering using a transition between different vertical arrangements of dots in multistacks, shifting quantum dot optical spectra towards longer wavelengths via activated alloy phase separation in the cap layer, and defect reduction techniques using a multiple cycle of partial overgrowth and thermal etching of the dots. For the In(Ga)As/GaAs model system, a combination of the techniques is demonstrated which allows defect-free nanostructures on GaAs substrates emitting at the technologically important wavelength of 1.3–1.55 μm. Chapter 5 gives a brief overview of the development of quantum dot lasers. It is shown that the newcomers are now taking over from conventional quantum well lasers, thereby becoming the first successful example of a laboratory discovery pervading the whole of human society within the short period of one decade. The summary in Chap. 6 presents a prospective view of the future development of semiconductor nanotechnology.

The book results from long-term cooperation between the Instutut für Festkörperphysik, Technische Universität Berlin, and Abraham Ioffe Physical Technical Institute of the Russian Academy of Sciences, St. Petersburg. The work of the two teams would not have been possible without generous support from the Deutsche Forschungsgemeinschaft (Sbf 296), Bundesministerium für Bildung und Forschung (bmb+f), Competence Center for Nanooptoelectronics (NanOp), and the Russian Foundation for Basic Research. In particular, cooperation and exchange of scientists between the teams were supported by the Volkswagen Stiftung, the governments of Germany and Russia within the framework of their general science cooperation agreement, and INTAS. V.A. Shchukin personally acknowledges support from the Alexander von Humboldt Foundation in the form of a research fellowship and from the Russian Foundation for Promotion of Science via a grant for young researchers. N.N. Ledentsov was supported by the Deutsche Akademische Austauschdienst (DAAD) Guest Professorship program, the Alexander von Humboldt Foundation via donation of equipment, the Berlin-Brandenburg Academy of Sciences and the Peregrinus-Stiftung (Rudolf Meimberg). We could not have carried out the research or written this book without their help and are therefore very grateful to the respective administrations and many anonymous referees who approved the project.

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