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Preface and Summary

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Abstract. Semiconductor nanostructures are ideal systems to tailor the physical properties via quantum effects, utilizing special growth techniques, self-assembling or lithographic processes in combination with tunable external electric and magnetic fields. We will call such systems "Quantum Materials".

The physical properties of these systems are governed by size quantization effects and discrete energy levels. The charging is controlled by the Coulomb blockade and it is possible to realize systems with N = 1,2,3 electrons, which allows one to study single particle effects and successively the developement of the most elementary many-body effects like the formation of singlet and triplet states, exchange and correlation.

An important aspect of these quantum materials is that it is possible to also manipulate the spins of the system, which directly relate the quantum materials to the strongly developing field of spintronic. In quantum materials, not only the electronic properties, but also the phonon spectrum will be quantized and confined optical and acoustic phonons can be studied. In addition the high quality of man made quantum dots also allows one to study the influence of size quantization on the crystal morphology and the formation of bulk, interface and surface states.

In this book we will cover in different chapters the preparation of quantum materials, a wide variety of experimental techniques for the investigation of these interesting systems and describe selected experiments which give an overview about the wide field of physics and chemistry that can be studied in these systems. These experiments benefit in an interacting way from sophisticated theoretical concepts that will be addressed in a number of chapters.

1.1 Preparation

In several chapters we will describe different methods to fabricate quantum materials. We will review the growth of optimized GaAs or InAs quantum wells and heterostructures by molecular beam epitaxy (MBE) with or without modulation doping. Starting from such two-dimensional electron systems (2DES), 1D quantum wires, 0D quantum dots or antidots can be prepared in a top-down process using etching techniques. We will also address MBE based bottom-up approaches for the preparation of self-assembled InAs quantum dot utilizing the Stranski-Krastanov growth mode or droplet epitaxy. Very important is also the preparation of contacts to the low-dimensional systems, in particular to control the spin orientation in all-semiconductor devices or in hybrid ferromagnetic/semiconductor systems. The MBE also allows one to grow strained bi-layer system which roll up to microrolls if a sacrifying layer is etched away. In such microrolls it is possible to confine light or to study the quantum Hall effect in a curved geometry.

Another powerful bottom-up process for the fabrication of quantum materials is the wet chemical synthesis of nanocrystals. It is possible to prepare sophisticated core-shell-shell quantum dots and nanocrystals with very narrow size distributions, high stabilities and photoluminescence yields.

1.2 Experimental techniques

In a number of chapters we will give introductions into various experimental techniques to study quantum materials. With far infrared, photoconductivity and Raman spectroscopy the elementary charge density and spin excitations in quantum wells, wires, dots and antidots can be studied. Photoluminescence in the visible and near infrared regime gives access to excitronic excitations in the quantum materials, in particular, sophisticated set ups make it possible to perform spectroscopy on a single quantum dot revealing extremely narrow intrinsic line widths. X-ray spectroscopy is an element specific excitation which allows distinguishing between bulk, interface and surface states in nanocrystals and clusters. X-ray diffraction and near edge X-ray absorption fine-structure spectroscopy give access to the interplay of electronic structure, crystal morphology and the crystal's phase.

Cantilever magnetometry, capacitance-voltage and deep-level-transient-spectroscopy measure the ground state properties and density of state in the quantum structures. They are closely related and complementary to transport experiments on the same structures. A very powerful method for quantum materials is the scanning tunneling spectroscopy. On surfaces, step edges or quantum dots one can study the local density of states of electrons and holes in different dimensions and directly map the electron's wave functions in quantum dots and nano crystals.

1.3 Experiments and Theory

The focus in most of the chapters in this book lies on selected striking experiments and sophisticated theories for these quantum materials which are described in more detail in the following extended abstracts. In this summary we will briefly give some examples:

Self-assembled InAs quantum dots, embedded in gate structures, can be successively charged with N = 1,2,3 electrons. This charging is governed by the Coulomb blockade and can be studied by capacitance-voltage spectroscopy. With resonant Raman spectroscopy one observes for N = 1 electron directly the quantized energy levels of the systems. The spectra for N = 2 electrons, the so called quantum-dot Helium, are very different. One finds now besides singlet-singlet transition, the dipole-forbidden spin-density excitation into the triplet state. The latter resembles the ortho-Helium state of the natural He atom. A complementing approach to the energy levels of such artificial He atom comes from scanning electron tunneling spectroscopy which also allows the mapping of the individual electronic wave functions. Other approaches with complementary information arise from magnetization and deep-level-transient-spectroscopy.

An interesting feature of the quantum materials is the possibility to control the spin. In several chapters we will review theory and experiments of different aspects of spin transport, in particular, the controlled spin injection from hybrid ferromagnetic/semiconductor contacts or all-semiconductor spin valves based on the Rashba effect.

With sophisticated wet chemical synthesis it is possible to fabricate high quality quantum dots, in particular core-shell-shell systems with extraordinary photoluminescence fields and stabilities. This can be further improved by an integration into a block polymer matrix which provides an environment with well defined ligands. In such core-shell-shell structures it was possible to perform single-dot photo luminescence spectroscopy and observe very narrow side lines from confined acoustic and optical phonons of a single dot.