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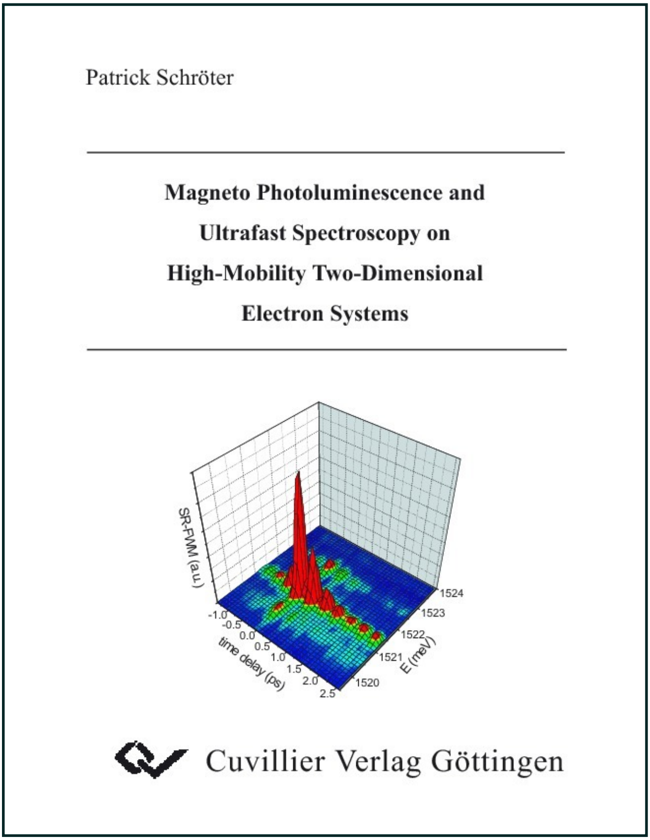
Magneto Photoluminescence and Ultrafast Spectroscopy on High-Mobility Two-Dimensional Electron Systems



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Chapter 1

Introduction

The development of new technologies is still driven by the research for new devices that are faster and smaller. Integrated circuits nowadays work in the gigahertz regime, corresponding to switching times in the order of nanoseconds. The optronic is a field of growing interest for even faster devices with even higher packing density. Here, instead of electrons and holes in semiconductor electronics, photons are used to carry the information. Electromagnetic waves have the advantage of interacting much less with each other, so that in the data transmission field for instance data can be packed more densely. Furthermore, switching times in the order of picoseconds can be obtained.

Still we are far from optronic devices, that process data only by photons, substituting our electronic devices. Nowadays many existing applications use the synergy of well known electronic devices and the advantages of photons. This of course requires a transformation between electronic and photonic signals and, necessarily, a deep understanding of the interaction processes between matter and light on the very short time scale. The electronic devices are continuously improved to higher processing rates as well. This also requires the understanding of carrier properties in very short time scales.

This work will concentrate on the GaAs/AlGaAs semiconductor system. High quality heterotructures of these materials can be created by molecular beam epitaxy and are commonly used for optical applications, such as semiconductor lasers and high frequency devices. The high electron mobility transistor (HEMT) is a common high frequency device that can today be found in mobile phones and satellite receivers. For basic research, these GaAs/AlGaAs heterostructures are an ideal system for probing quantum effects of confined electron gases.

If the semiconductor is excited optically, electron-hole pairs are created. This yields that in optical measurements on GaAs structures always the contributions of holes in the complicated valence-band have to be included. Photoluminescence (PL) spectroscopy is one of the main optical research methods in the investigation of low-dimensional heterostructures. The PL signal results from recombination of excited carriers and is mainly determined by the bandgap of the semiconductor. The quantum confinement in well structures leads to quantized states so that well parameters, as for instance the width, can be derived from the PL transition energy. Another powerful optical method is the absorption experiment that allows determination of the transition strengths of the excitations. With absorption the unoccupied states are investigated, while one can observe PL recombination only from occupied states. Thou these two methods complement one another. With a pulsed excitation, time-resolved experiments can also be performed. One simple method is for instance the measurement of PL emission for different times after excitation. With it, the lifetime of states can be investigated. More sophisticated, but also more powerful are time-resolved measurements that take advantage of nonlinearities within the medium. Over the last years, Four Wave Mixing (FWM) experiments became a common technique for the investigation of coherence properties of semiconductor heterostructures. In heterostructures these non-linearities are usually very small so that mainly undoped multilayer structures have been studied. The strong transitions of excitons, bound complexes of conduction band electrons and valence band holes, can be observed in undoped structures. Because of confinement, the separation of carriers in low dimensional structures is reduced and the binding of the excitons is enhanced. By modulation doping of the GaAs/AlGaAs heterostructures, a two-dimensional electron gas (2DEG) can be created. The 2DEG screens the electron-hole interaction and, consequently, for high electron densities no exciton states can form. For low electron densities, not only charge neutral excitons but also charged-exciton states can be observed. It is assumed that an additional electron polarizes the neutral exciton state and so becomes bound. But the process of the charged exciton formation is up to now not very well understood. It is mostly assumed that the observed triplet states are localized [1, 2, 3]. Without applied magnetic field the charged-exciton singlet state is the ground state. This state forms by antiparallel spin wave functions of the electrons and a symmetrical spatial wave function, so the total antisymmetrical wave function for fermions is fulfilled. In magnetic fields also triplet states can become bound. The triplet state has parallel electron spin wave functions and so must have an antisymmetrical spatial wave function.

In this work the optical measurements on high-mobility, modulation-doped GaAs/AlGaAs heterostructures will be discussed. PL measurements are performed at very low temperatures of about 80 mK and at magnetic fields up to 14 T. The electron density of the sample can be tuned with a metallic gate electrode so that also the regime of the charged excitons can be investigates using the same sample. With another gate electrode also the bending of the conduction and valence band along the growth direction can be varied. By increasing this tilting, the electron and hole layers become increasingly confined towards the quantum-well interfaces and the separation of electrons and holes is increased. Szlufarska *et al.* calculated that an unbinding of the optically allowed charged-exciton states already for small separations should occur [4]. Only few results exist that study the influence of the carrier-layers separation on the exciton binding. The increased separation of electron and hole layer also changes the observed PL spectra for high electron densities. This allows one to assign observed deviations from the single particle Landau-level picture to the changed electron-hole interaction.

These high-mobility samples are also investigated by time-resolved experiments. At low temperatures a transition is observed that can not clearly be assigned. The time-resolved measurements emphasize that this transition can be attributed to recombination with a light-hole like state in magnetic fields. For a better alignment of weak FWM, a specially designed sample was grown, that is very similar to the modulation-doped sample for the milli-Kelvin experiments. An undoped multiple-well structure was additionally inserted below the doped quantum well. For this sample, time-resolved measurements show that the triplet exciton in this high-mobility sample is most probably not localized. Furthermore, an unusual beating behavior of the observed neutral-exciton states was found.

Chapter 2 of this work gives a brief overview of the material system and the 2DEG properties. Afterwards the interaction with light by linear and nonlinear processes is explained, followed by a short overview of the different time regimes and the relaxation processes of excited carriers.

In Chapter 3, the designs of the MBE grown wafers used in this work are presented. The undoped sample is grown in Hamburg, while the high-mobility modulation-doped samples are grown in Munich and Regensburg. Afterwards, the preparation steps for the samples are explained.

In Chapter 4, the experiments in the milli-Kelvin setup are discussed. First, the experimental setup is explained, followed by PL-results without magnetic field. Second, the results at high 2DEG electron densities and of the strongly depleted system, exhibiting charged and neutral excitons, are presented.

Chapter 4 shows the time-resolved experiments and again first the experimental setup is explained. The following three sections concentrate on the three different wafers: first time-dependent measurements for an undoped multiple-quantum structure are explained followed by the results on the two modulation-doped samples.

Chapter 5 summarizes this work.

Chapter 2

Physical background

In this chapter, the physical background is given. The properties of the three-dimensional GaAs and AlGaAs crystal are briefly presented first, followed by the general and in particular the optical behavior of two-dimensional electron systems.

2.1 Bulk material

The III-V compound semiconductors GaAs and AlAs crystallize in the zinc-blende structure. This lattice is formed by two *fcc*-lattices, each built up by gallium or aluminium and arsenic, and shifted by (1/4,1/4,1/4) of the lattice constant a. At room temperature this lattice constant is $a_{GaAs} = 0.5655\,\mathrm{nm}$ for GaAs and $a_{AlAs} = 0.5661\,\mathrm{nm}$ for AlAs. It only differs by 0.1% for these compound semiconductors.

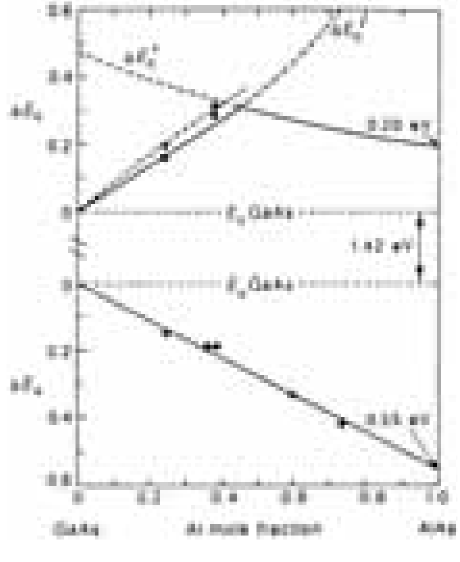

Figure 2.1: Development of the conduction- and valance-band edge by increasing the mole fraction x in $Al_xGa_{1-x}As$. For $x > 0.45$ the bandgap is indirect. [5]