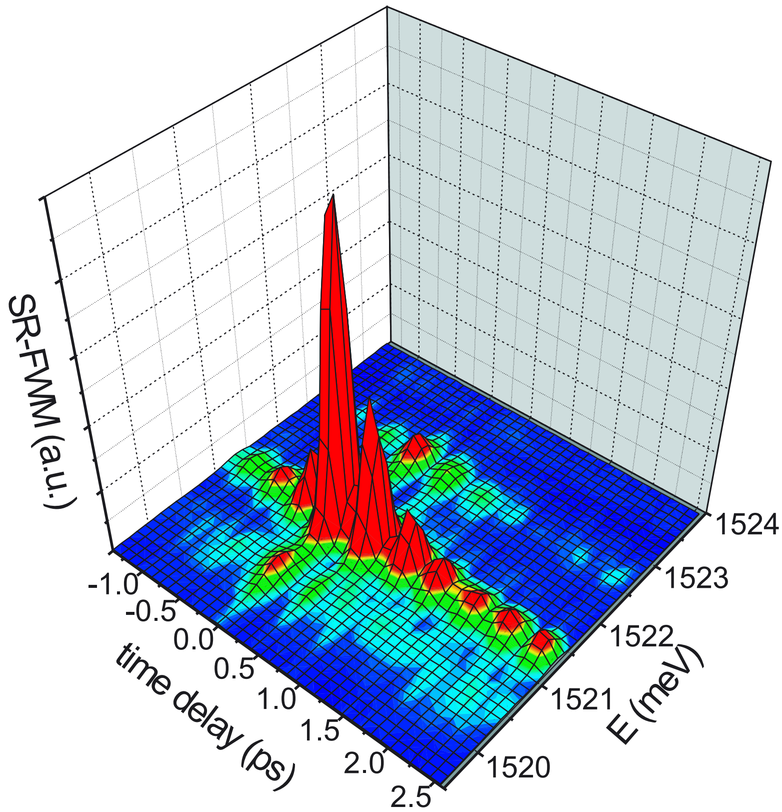
Patrick Schröter

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



Cuvillier Verlag Göttingen

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

Dissertation
zur Erlangung des Doktorgrades
des Fachbereichs Physik
der Universität Hamburg

vorgelegt von

Patrick Schröter

aus Hamburg

Hamburg

2004

Bibliografische Information Der Deutschen Bibliothek
Die Deutsche Bibliothek verzeichnet diese Publikation in der Deutschen Nationalbibliografie; detaillierte bibliografische Daten sind im Internet über http://dnb.ddb.de abrufbar.
1. Aufl. - Göttingen : Cuvillier, 2004
Zugl.: Hamburg, Univ., Diss., 2004
ISBN 3-86537-231-7

Gutachter der Dissertation:	Prof. Dr. D. Heitmann Prof. Dr. D. Pfannkuche
Gutachter der Disputation:	Prof. Dr. D. Heitmann Prof. Dr. W. Hansen
Datum der Disputation:	10. August 2004
Vorsitzender des Prüfungsausschusses:	Dr. D. Grundler
Vorsitzender des Promotionsausschusses:	Prof. Dr. R. Wiesendanger
Dekan des Fachbereichs Physik	Prof. Dr. G. Huber

⊕ CUVILLIER VERLAG, Göttingen 2004
Nonnenstieg 8, 37075 Göttingen
Telefon: 0551-54724-0
Telefax: 0551-54724-21
www.cuvillier.de

Alle Rechte vorbehalten. Ohne ausdrückliche Genehmigung des Verlages ist es nicht gestattet, das Buch oder Teile daraus auf fotomechanischem Weg (Fotokopie, Mikrokopie) zu vervielfältigen.
1. Auflage, 2004
Gedruckt auf säurefreiem Papier

ISBN 3-86537-231-7

Abstract

This thesis presents magneto photoluminescence and ultrafast spectroscopy experiments on high-mobility two-dimensional GaAs single quantum-well structures. Using a milli-Kelvin setup, we are able to perform photoluminescence measurements at temperatures of down to 80 mK. For the ultrafast setup, the focus lies on the spectrally-resolved Four Wave mixing experiments. With this technique, the coherence of the photo-excited carriers is investigated time-resolved. From it, conclusions can be drawn on the correlations between the carriers in the system.

In the experiments the electron density of the high-mobility samples is tunable with a metallic gate, so the 2DEG at small filling factors as well as the regime of the charged and neutral excitons can be investigated. For these high-mobility samples, it can be expected that only few imperfections exist, so that the correlations between electrons and holes can excellently be studied.

For the experiments at milli-Kelvin temperatures, along the growth direction an electric field can be applied with a back-gate electrode. This allows us to study many-particle effects dependent on the distances between electrons and holes. Especially the Fermi-edge singularity and the low energy broadenings of the photoluminescence lineshapes at odd filling factors $\nu = 3$ and $\nu = 1$ are investigated in the high electron density regime. Moreover, in magnetic fields an additional transition is observed down to $\nu = 1$ that is attributed to a light-hole like state. For large electron-hole distances, the observed transitions in the low carrier-density regime are assigned to neutral exciton states that have strong contributions of single-particle like transitions.

In this work, the focus of the time-resolved experiments is on the modulation-doped single-well structures. These are of high-quality but have the disadvantage that they only exhibit weak Four Wave Mixing signals. Up to now, only results on the doped multiple well structures exist. A main part of the Four Wave Mixing experiments focuses on the two-dimensional electron gas at filling factor $\nu = 1$. With increasing magnetic field a step-like increase of the dephasing time at $\nu = 1$ is found for the light-hole like transition. Moreover, it is deduced that the dephasing time not only depends on the electron states but also on the coupling between the hole states. A sample structure is introduced, specially designed for our time-resolved experiments, that provides for weak signals the necessary prealignment of the setup. On these samples, also circular polarization resolved measurements could be performed. In these experiments, no signature of filling factor $\nu = 1$ is resolved in the dephasing time. From the dephasing times of the excitons, it is concluded that the charged exciton is probably not localized in our sample. Moreover, an interchanged beating pattern of the neutral excitons with the triplet state is observed.

Inhaltsangabe

In dieser Arbeit werden Magneto-Photolumineszenz und Ultrakurzzeit Spektroskopie-Experimente an hochbeweglichen zweidimensionalen GaAs Einzel-Quantentopfstrukturen vorgestellt. Mit einem Milli-Kelvin Aufbau können Photolumineszenzexperimente bei Temperaturen bis hinab zu 80 mK durchgeführt werden. Bei dem Ultrakurzzeit-Aufbau liegt das Hauptaugenmerk auf den Vier-Wellen-Misch Experimenten, die die Untersuchung der Kohärenzzeiten der photoangeregten Ladungsträger ermöglichen. Es lassen sich daraus Rückschlüsse über die Korrelationen zwischen den Ladungsträger im System ziehen.

In den Experimenten kann die Elektronen Ladungsträgerdichte mit einem metallischen Gate durchgestimmt werden, so dass das zweidimensionale Elektronengas bei kleinen Füllfaktoren sowie der Bereich der geladenen und neutralen Exzitonen untersucht werden kann. Die hohe Qualität der Proben lässt erwarten, dass es nur wenige Fehlstellen gibt, so dass die Korrelationen zwischen den Elektronen und Löchern hervorragend untersucht werden können.

Bei den Experimenten bei Milli-Kelvin Temperaturen kann mit einer Rückkontakt Elektrode ein elektrisches Feld entlang der Wachstumsrichtung angelegt werden. Dieses erlaubt die Untersuchung von Vielteilcheneffekten in Abhängigkeit vom Abstand der Elektronen und Löcher. Im hohen Ladungsträgerdichtebereich werden insbesondere die Fermikanten-Singularität und niederenergetische Verbreiterungen der Photolumineszenzlinien bei ungeraden Füllfaktoren $\nu = 3$ und $\nu = 1$ untersucht. Desweiteren wird bei Messungen im Magnetfeld ein zusätzlicher Übergang bis hinab zu Füllfaktor $\nu = 1$ beobachtet, der einem Leichtloch-ähnlichen Übergang zugeordnet wird. Für große Elektronen-Loch Abstände werden die im niedrigen Ladungsträgerdichtebereich beobachteten Übergänge neutralen Exzitionen zugeordnet, die starke Anteile von Einteilchen-Übergängen haben.

Die zeitaufgelösten Messungen in dieser Arbeit behandeln for allem die Messungen an modulationsdotierten Einzel-Topf Strukturen. Diese sind von hoher Qualität, haben jedoch den Nachteil, dass sie nur schwache Vier-Wellen-Misch Signale aufweisen. Bis heute gibt es nur Ergebnisse von dotierten Mehrfach-Töpfen. Ein großer Teil dieser Arbeit konzentriert sich auf die Vier-Wellen-Misch Experimente am zweidimensionalen Elektronengas bei Füllfaktor $\nu = 1$. Mit zunehmenden Magnetfeld wird für den Leichtlochartigen Übergang ein stufenartiger Anstieg der Dephasierungszeit bei $\nu = 1$ beobachtet. Weiterhin konnte abgeleitet werden, dass die Dephasingszeit nicht nur von den Elektronenzuständen, sondern auch von der Kopplung zwischen den Lochzuständen abhängt. Es wird eine Probenstruktur vorgestellt, speziell entworfen für zeitaufgelösten Messungen, die die Vorjustage des Aufbaus auch für schwache Signale erlaubt. So konnten an diesen Proben auch zirkular polarisationsaufgelöste Messungen durchgeführt werden. In diesen Experimenten werden aber keine Anzeichen vom Füllfaktor $\nu = 1$ in der Dephasingszeit aufgelöst. Aus den Dephasierungszeiten der Exzitonen wird gefolgert, dass die geladenen Exzitonen in diesen Proben wahrscheinlich nicht lokalisiert sind. Desweiteren wird ein vertauschtes 'Beating'-Verhalten der neutralen Exzitonen mit dem Triplet Zustand beobachtet.

Contents

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 $a_{GaAs} = 0.5655\,\text{nm}$ for GaAs and $a_{AlAs} = 0.5661\,\text{nm}$ for AlAs. It only differs by 0.1% for these compound semiconductors.

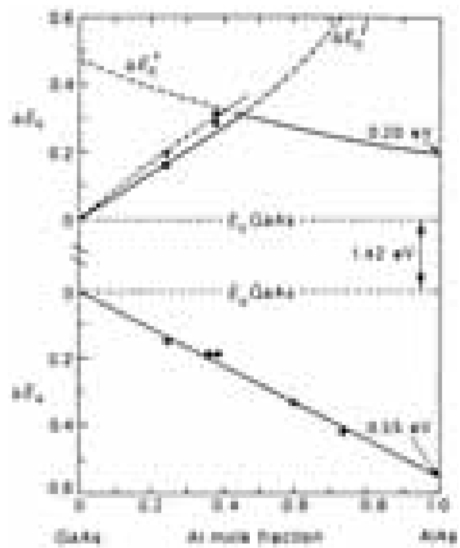


Figure 2.1: Development of the conduction- and valance-band edge by increasing the mole fraction x in $Al_xGa_{1-x}As$. For $x > 0.45$ the bandgap is indirect. [5]