

OPTICAL STUDIES OF MODULATION-DOPED V-GROOVE QUANTUM WIRES

JIN KIM

Clarendon Laboratory
Department of Physics
University of Oxford

Thesis submitted for the degree of
Doctor of Philosophy

Merton College
Trinity Term 2000



OPTICAL STUDIES OF MODULATION-DOPED V-GROOVE QUANTUM WIRES

Jin Kim

Merton College, Oxford

Abstract

Experimental studies of optical properties in undoped and modulation-doped v-groove quantum wires (QWR) are presented. The results show good agreement with theoretical predictions.

The investigation of undoped samples demonstrates the successful fabrication of high quality samples with small wire dimensions, exhibiting narrow linewidths and large subband spacings. Calculations from the Schrödinger solver show good agreement with the experimental results. Information about the shape of the confining potential is obtained from magneto-optical measurements where anisotropic shrinkage and binding energies of the excitons are measured. In high excitation power experiments the suppression of the excitonic recombination is observed due to screening and phase space filling. Photoluminescence excitation experiments reveal an inefficient carrier intersubband relaxation.

Extending the optical investigations to modulation-doped samples, the formation of a one-dimensional electron gas can be observed. As a strong indication for this is the presence of a Fermi edge singularity (FES). Furthermore, Poisson-Schrödinger calculations show that the increased electron density in the conduction band leads to modified confinement energies. This was confirmed in magneto photoluminescence (MPL) experiments, where the diamagnetic shift of the luminescence from the first excited state is stronger than in the undoped case, as the state is squeezed further into the corners of the QWR. Recombination of the ground state electrons with different hole states appears as a fine structure in MPL spectra.

Detailed analysis provides clear evidence of the FES. The expected temperature sensitivity of the FES is observed for lattice and electron heating. The FES intensity is also reduced at high excitation powers. The role of hole localisation and subband coupling is discussed. At applied magnetic fields the coupling of bands induces an enhancement of the singularity.

Finally, the behaviour of hot carriers is investigated with time-resolved and electro-photoluminescence measurements. Long luminescence lifetimes indicate that electron-hole separation occurs due to the pinch-off between the QWR and the side quantum well. The field dependence of the electron heating shows quite clearly that LO phonon scattering is the dominant relaxation process at electron temperatures above ~40 K.

To my parents

Acknowledgements

I would like to gratefully acknowledge:

Prof. John F. Ryan for his scientific supervision and support throughout my work;

The European Commission and the Deutscher Akademischer Austauschdienst for funding my studies;

Dr. Angela Maciel for teaching me the basics of optical spectroscopy and Dr. Robert Taylor for repeatedly helping me out with his vast knowledge of experimental physics;

Dr. Eoin O'Sullivan for his competent insights into semiconductor theory and being always very helpful and Dr. Hugh Davies for sharing his expertise on magnetic experiments;

Prof. Hans Lüth, Dr. Thomas Schäpers, Dipl. phys. Axel Schwarz, Dipl. phys. Andreas Kaluza and Christel Dieker from the Institut für Schicht- und Ionentechnik, Forschungszentrum Jülich, for a fruitful and truly enjoyable collaboration;

Dipl. ing. Marc Hauert for always being such a considerate colleague and great friend;

Dr. Johan Fopma for his constructive co-operation in designing and building electronic devices;

The staff of the Clarendon Workshop for their great problem-solving abilities in repairing and constructing essential bits and pieces of experimental set-ups;

All members of the Quantum Optoelectronics Group for making the lab a human and friendly place;

Merton College for providing the best possible environment to pursue academic research and studies;

My parents for their love and support;

And He-Son for everything.

CONTENTS

1 Introduction	1
2 Properties of quantum wires	5
2.1 Introduction	6
2.2 Types of quantum wires	7
2.3 Conduction band in one-dimension	14
2.4 Valence band and interband optical transitions	19
2.5 Bandstructure calculations	23
3 Fabrication of v-groove quantum wires	30
3.1 Introduction	31
3.2 Pre-patterning	31
3.3 MOCVD growth.....	35
3.4 Metallization	37
3.5 Structural analysis	38
4 Experimental Arrangements	45
4.1 Introduction	46
4.2 Photoluminescence set-up	46

4.3	Time-resolved photoluminescence set-up.....	49
4.4	Electro-photoluminescence set-up	51
4.5	Magneto-photoluminescence set-up.....	53
4.6	Photoluminescence excitation set-up	53
4.7	Magneto-transport measurements set-up	56
5	Optical properties of undoped v-groove quantum wires	58
5.1	Introduction	59
5.2	Optical properties of undoped samples	60
5.3	Results from the Schrödinger solver	67
5.4	Optical transitions in applied magnetic fields.....	69
5.5	High excitation power experiments	77
5.6	Photoluminescence excitation spectra.....	81
5.7	Conclusions and outlook	84
6	Optical properties of modulation-doped v-groove quantum wires	86
6.1	Introduction	87
6.2	Electronic states in modulation-doped samples	88
6.3	Magneto-optical experiments.....	103
6.4	Magneto-transport experiments	109
6.5	Conclusions and outlook	112
7	Fermi edge singularities	115
7.1	Introduction	116
7.2	Basic theory of Fermi edge singularities.....	117
7.3	Fermi edge singularities in photoluminescence spectra.....	120
7.4	Temperature dependence.....	120

7.5	Fermi edge singularity in a magnetic field.....	123
7.6	Discussion	125
7.7	Conclusions and outlook	129
8	Hot electrons in modulation-doped v-groove quantum wires	130
8.1	Introduction	131
8.2	Time-resolved photoluminescence experiments	132
8.3	Electro-photoluminescence experiments	137
8.4	Conclusions and outlook	147
	Appendix	149
	Bibliography	153

PUBLICATIONS

JOURNALS

1. **Electron states, magneto-transport and carrier dynamics in modulation-doped v-groove quantum wires**, A.C. Maciel, J. Kim, J.F. Ryan, A. Schwarz, Th. Schäpers, Ch. Dieker, H. Hardtdegen, H. Lüth, *Solid-State Electronics*, **42**, 1245 (1998)
2. **Hot electrons in modulation-doped GaAs v-groove quantum wires**, A. C. Maciel, J. Kim, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, Th. Schäpers, D. Meertens, Ch. Dieker, H. Lüth, *Physica B* **272**, 101, (1999)
3. **Fermi-edge singularities in the photoluminescence and magneto-optical spectra of modulation-doped v-groove quantum wires**, A. C. Maciel, J. Kim, H. D. M. Davies, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, Th. Schäpers, D. Meertens, Ch. Dieker, H. Lüth, *Physica B* **272**, 101 (1999)
4. **Electron transport in modulation-doped GaAs v-groove quantum wires**, A. Schwarz, A. Kaluza, Th. Schäpers, H. Hardtdegen, H. Lüth, D. Meertens, Ch. Dieker, A. C. Maciel, J. Kim, E. D. O'Sullivan, J. F. Ryan, *Physica E* **7**, 760 (2000)
5. **Fermi-edge singularities in the photoluminescence spectrum of modulation-doped GaAs v-groove quantum wire**, J. Kim, A. C. Maciel, H. D. M. Davies, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, D. Meertens, Ch. Dieker, Th. Schäpers, H. Lüth, *Physica E* **6**, 530 (2000)

CONFERENCES

1. **Carrier relaxation and localisation in v-groove quantum wires**, R. Roshan, M. Hauert, J. Kim, A.C. Maciel, J.F. Ryan, A. Schwarz, A. Kaluza, Th. Schäpers, H. Lüth, Proceedings of ICPS 2000, Osaka
2. **Near-field spectroscopy of Fermi-edge singularity in single modulation-doped v-groove quantum wires**, M. Hauert, R. Roshan, A.C. Maciel, J. Kim, J.F. Ryan, A. Schwarz, A. Kaluza, Th. Schäpers, H. Lüth, Proceedings of ICPS 2000, Osaka
3. **Scanning near-field optical spectroscopy of buried semiconductor heterostructures**, M. Hauert, R. Roshan, A.C. Maciel, J. Kim, J.F. Ryan, A. Schwarz, A. Kaluza, Th. Schäpers, H. Lüth, Proceedings of ICPS 2000, Osaka

CHAPTER 1

INTRODUCTION

The fast development of the internet in recent years has demonstrated the demand for novel and more efficient communication channels and thus the need for high-performance hardware to build the technological infrastructure. Micro- and optoelectronics have been key-technologies in developing high-frequency transistors for wireless appliances and components for broadband optical fibre networks. Major objectives of the semiconductor research in these fields are to increase the speed and reduce the size of electronic chips and produce highly efficient lasers and detectors for optical networks.

One way to achieve these goals is to reduce the size and the dimension of the semiconductor structures. The three- (3D) and two-dimensional (2D) devices, which are largely used to date, have been made smaller to an extent that physical limits are reached, where a reliable performance can be jeopardized. However, early theoretical predictions have shown that one- (1D) and zero-dimensional (0D) semiconductor structures could result in superior devices with improved electronic and optical properties.

In 1D semiconductor structures, also called quantum wires (QWRs), singularities in the density of states are expected to yield higher emission efficiency in laser structures [Kapon 1989] and the reduced phase space to greatly enhanced mobilities [Sakaki 1980]. One of the most promising methods to produce QWRs is the v-groove technology [Kapon 1987].

v-shaped grooves with (111)A facets are etched into a (001)-GaAs substrate which is then overgrown using organo-metallic chemical vapour deposition or molecular beam epitaxy. There, GaAs/AlGaAs-QWRs are generated by self-organised growth in the grooves. This epitaxial process ensures a good homogeneity in down to a few nm thin structures, in contrast to other methods where for example etching is used to patterning the wires. Moreover, interface defects caused by etching are avoided and thus degradation of optical and electrical properties [Clausen 1989]. v-groove QWR laser structures have already shown higher quantum efficiency and lower threshold currents than in bulk or quantum wells [Simhony 1991, Tiwari 1994].

To achieve high carrier concentrations for device purposes, the study of doping and its effects is essential. Modulation-doping is a technique where a doping layer is introduced in the barrier material separated from the quantum well channel by a spacer layer. The dopant carriers relax into the wider band-gap material, increasing the carrier density while the scattering rates are strongly reduced compared to direct doping. This is expected to lead to significantly higher mobilities and increased radiative recombination efficiencies.

This work investigates undoped and modulation-doped v-groove QWRs by means of optical spectroscopy. The understanding of the optical properties is complemented by structural analysis, electrical measurements, and supported by numerical simulations. The goal of this work was to assess the basic properties of such structures and investigate properties which had been predicted for doped QWRs, like Fermi edge singularities.

Chapter 2 - Properties of quantum wires

To begin with the major types of QWRs will be briefly described, including the fabrication processes and their advantages and disadvantages. In chapter 2.2 the basic optical properties of QWRs will be discussed and derived from fundamental theoretical considerations, including subbands, density of states and valence band mixing. In 2.3 band structure models

for v-groove QWRs will be presented. In particular the self-consistent Poisson-Schrödinger solver is elaborated on, which was applied to sample geometries investigated in this work.

Chapter 3 - Fabrication of v-groove quantum wires

In chapter 3 the fabrication and the structural analysis of the v-groove QWR samples are presented. The fabrication involves a sophisticated combination of pre-patterning and epitaxial growth of the heterostructure in a metallo-organic vapour deposition system. Structural analysis was conducted using scanning and transmission electron microscopy.

Chapter 4 - Experimental arrangements

The various experimental set-ups used for the optical spectroscopy in this work are presented in this chapter. They include the time-integrated and time-resolved photoluminescence (PL) set-ups as well as the electro-optical (electro-PL), magneto-optical (magneto-PL) and PL excitation (PLE) arrangements. Details about the lasers used, cryogenic and detection systems are given as well.

Chapter 5 - Undoped v-groove quantum wires

Undoped v-groove QWRs were grown in series with doped samples using comparable parameter to serve as reference samples: the investigation of these samples is presented in this chapter. It comprises optical characterisation of the different parts of the structure with PL, cathodoluminescence (CL), magneto-PL (MPL) and PL excitation (PLE) spectroscopy. The improved undoped sample exhibits sharp excitonic luminescence peaks, indicating a high structural quality. The energy levels in the QWR found by PL measurements are consistent with results from the Poisson-Schrödinger simulation. At high excitation levels suppression of the excitonic recombination due to screening of the electron-hole interaction and phase space filling can be observed. MPL provides information about the form of the 1D

confining potential. In PLE experiments it is discovered, that intersubband relaxation is inhibited at low temperatures.

Chapter 6 - Modulation-doped v-groove quantum wires

Analogous to chapter 5, basic optical properties of doped samples are investigated with optical spectroscopy and analysed with the help of numerical simulations. The results are compared with each other yielding information about the effect of doping. The successive improvement of the fabrication on the basis of optical investigations has lead to successfully modulation-doped and high quality samples. Careful analysis of the transitions in the QWR has even identified a Fermi edge singularity, which had been predicted in doped one-dimensional semiconductor structures. Some other interesting findings originate from MPL experiments. They reveal the change in charge distribution in the QWR with doping, as calculated with a Poisson-Schrödinger solver. Also, the appearance of hole states in high magnetic fields can be observed. The chapter ends with complementary magneto-transport measurements which yield information about transport channels and carrier densities.

Chapter 7 - Fermi edge singularities

The results of a detailed investigation of the Fermi edge singularity (FES) observed in a series of doped samples are presented in this chapter. First the origin of the FES is explained theoretically. In the following sections experimental results are presented which in particular consider the characteristic temperature sensitivity observed under lattice and electron heating. In magneto-optical experiments the influence of an applied magnetic field on the singularity reveals an enhancement due to strong subband mixing. The role of hole localisation for FES is an important issue and is discussed for the investigated samples.

Chapter 8 - Hot electrons

The physics of hot electrons in modulation-doped v-groove QWRs is discussed. The carrier relaxation in the QWRs probed by time-resolved PL show a prolonged lifetime due to the separation of electrons and holes while in systems with several occupied subbands a long lifetime originates from cooling of a thermalised electron-hole system. Finally, in electro-PL the energy loss mechanisms were investigated, revealing that LO phonon scattering is the main relaxation process for hot electrons in QWRs at carrier temperature > 40 K.

CHAPTER 2

PROPERTIES OF QUANTUM WIRES

CONTENTS

2.1	INTRODUCTION.....	6
2.2	TYPES OF QUANTUM WIRES	7
2.3	CONDUCTION BAND IN ONE-DIMENSION	14
2.4	VALENCE BAND AND INTERBAND OPTICAL TRANSITIONS	19
2.5	BANDSTRUCTURE CALCULATIONS	23

2.1 INTRODUCTION

This chapter will first give a brief overview of the major types of quantum wires (QWRs) and explain the major advantages and disadvantages of the corresponding fabrication methods. In order to understand the optical properties of 1D structures one has to study the bandstructure modified by the 2D confinement. The conduction band for a 1D structure will be explained in chapter 2.2, deriving quantities such as subbands and density of states. In the next section the complicated valence band structure and optical transitions expected in QWRs will be explored. Finally theoretical models are presented, which are used in simulations in order to calculate energy levels in v-groove QWRs specifically.

2.2 TYPES OF QUANTUM WIRES

Various fabrication methods have been employed to fabricate 1D semiconductor structures. Some of the popular techniques are fine etching of QWs, growth on non-planar or tilted substrates and overgrowth on cleaved-edge surfaces. The ideal method would allow a good control of the wire width and thickness down to a few nanometers and produce smooth and uniform interfaces with the barrier material. None of the growth methods used to date have produced the perfect QWR, but many have been employed successfully to investigate different aspects of the physics in 1D structures.

(a) v-groove quantum wires and related structures

v-groove QWRs are self-organised structures fabricated by epitaxial growth of semiconductor layers on pre-patterned substrates. v-grooves of a few μm width and separation are etched into a (100) GaAs substrate using a SiO_2 -etch mask [Schäpers 1987] or a holographic pattern [Kapon 1987] (fig. 2.1 (a)). The pre-patterned substrate is then overgrown with a sequence of GaAs and AlGaAs layers similar to that for producing a QW,

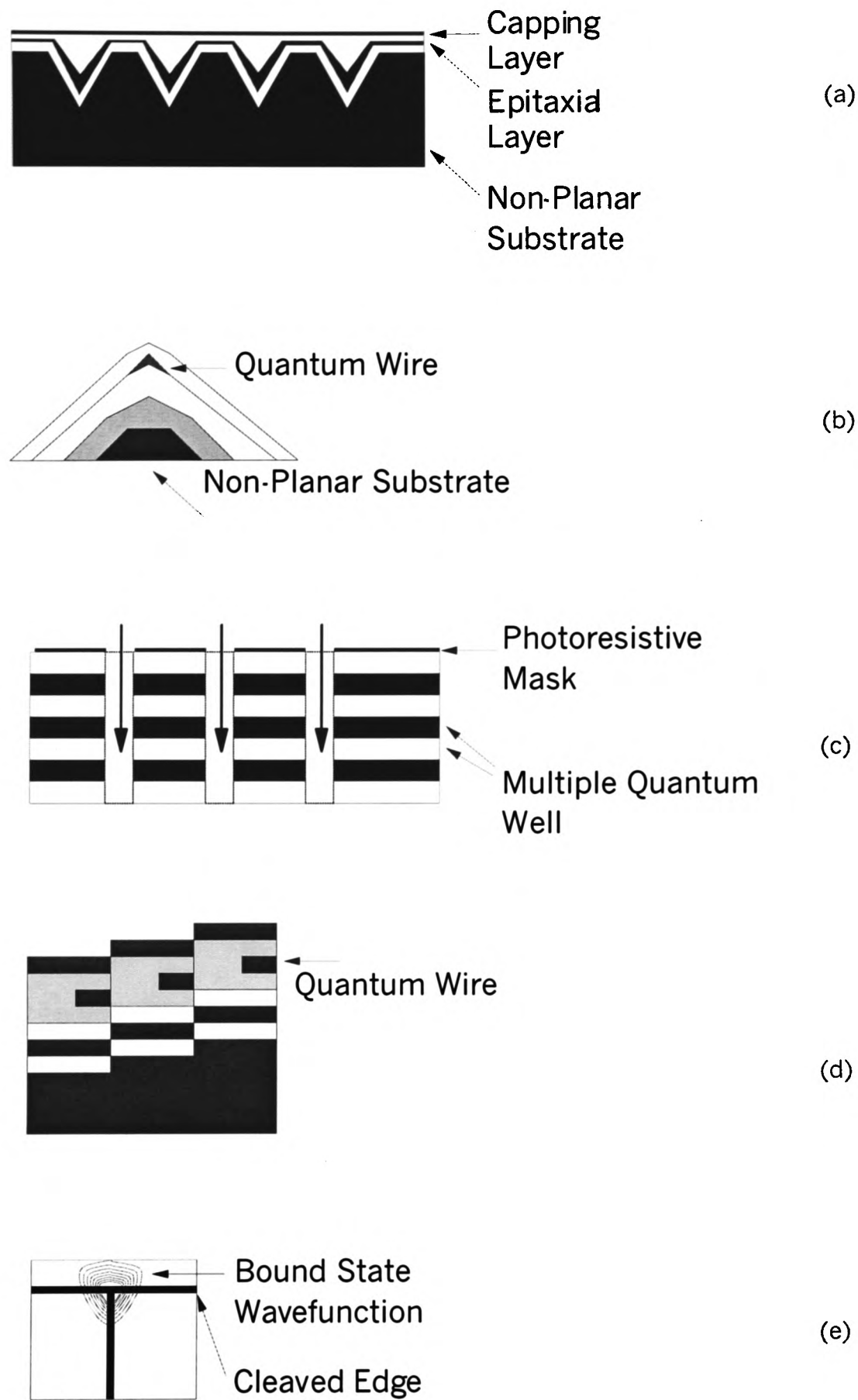


Figure 2.1: *Types of quantum wires.* (a) v-groove quantum wire ($3 \times 10 \text{ nm}^2$) (b) ridge-edge quantum wire ($5 \times 20 \text{ nm}^2$) (c) etched quantum wires ($10 \times 30 \text{ nm}^2$) (d) quantum wires on vicinal- surfaces ($4 \times 4 \text{ nm}^2$) (e) cleaved overgrown T-quantum wires ($3 \times 3 \text{ nm}^2$). Typical wire dimensions given in brackets.

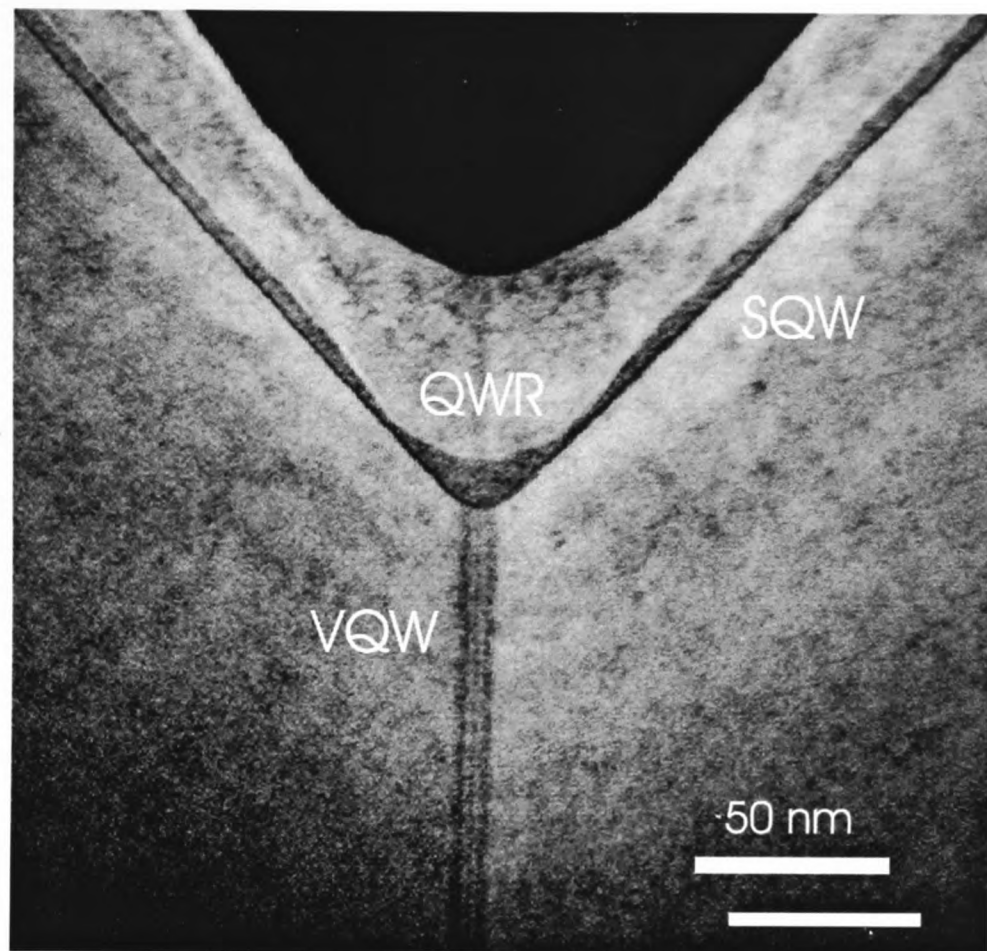


Figure 2.2: *Cross-section transmission electron microscopy picture of a v-groove quantum wire. The quantum wire (QWR) is separated by a pinch-off from the side quantum well (SQW). The thickness of the SQW in this sample is 10 nm while the QWR is about 15 nm thick and 40 nm wide. The vertical quantum well (VQW) is a Ga-rich quantum well-like region which is due to preferential growth of GaAs on certain facets on the bottom of the v-groove.*

using metal organic chemical vapour deposition (MOCVD) or molecular beam epitaxy (MBE).

On the bottom of the v-groove the GaAs grows thicker due to a preferential growth on the narrow (100) facet resulting in a wire-like structure along the groove with a crescent shape cross section (fig. 2.2). Another typical feature of the v-groove QWR is the side quantum well (SQW), which grows on the (111)A slopes of the v-groove and has the physical properties of a QW. The SQW and the QWR are connected through a pinch-off which

separates the 2D from the 1D region. Depending on the Al-sources used for growing the AlGaAs layer, the barrier can show a so-called vertical quantum well (VQW), which is GaAs-rich, a QW structure in the centre of the groove along the growth direction. A detailed description of the fabrication method will follow in chapter 3.

The v-groove QWR exhibits smooth interfaces with the barrier material and the thickness of the QWR can be adjusted with monolayer precision. The disadvantage of this method is that the QWR is laterally formed by a pinch-off towards the 2D SQW and strictly yields only a *quasi*-1D structure. However, with improving processing and growth techniques it has been possible to achieve pinch-offs half as thick as the SQW, which therefore represent an effective potential barrier to the QWR. The thickness of the SQW shown in fig. 2.2 is 5 nm, the QWR thickness 15 nm while the pinch-off is thinner than 3 nm. The potential difference between the SQW and the pinch-off region for the valence and the conduction band together can be estimated to about 100 meV while between the QWR and the pinch-off region yields about 177 meV¹.

With epitaxial growth it is straight-forward to produce vertically stacked QWR layers. A very common arrangement are double wires, where two QWRs are grown on top of each other. These structures are suitable for investigating coupling mechanisms of the electron states in the two QWRs [Roskos 1992].

To fabricate ridge QWRs (fig. 2.1 (b)), grooves are etched into a GaAs substrate, like for v-groove QWRs, but with a smaller groove spacing so that ridges are formed in the overgrowth process. Instead of generating the QWRs in the grooves, the goal is to grow them on the ridge [Okada 1997].

¹ A simple Kronig-Penny calculation was used which calculates confinement energies in superlattices. However, if the thickness of the barrier layer is made large, it gives a good approximation for single layer heterostructures.

(b) Etched wires

A more straightforward way to realize QWRs is to prepare a suitable stripe mask on top of a QW or multiple QW structure and to etch chemically or with an ion plasma (reactive ion etching) through the grown layers (fig. 2.1 (c)). This process is called deep etching or deep-mesa etching. After the etching the samples are overgrown in an epitaxy system [Petroff 1982, Stern 1984].

Such nanostructures suffer from damage at the side walls induced by the etching processes [Illing 1995] or dislocations. Although it has been possible to investigate certain aspects of electrical properties, the optical properties are often dominated by strain relaxation processes [Kümmell 1998]. While the thickness of the QWs can be controlled precisely and therefore the thickness of the QWR can be controlled in the growth direction, the lateral thickness is often non-uniform leading to inhomogeneous broadening of optical spectra. The QWR width is also limited by the capabilities of the lithography which is applied to produce the mask and are typically 200 nm or larger.

(c) Quantum wires on vicinal or corrugated surfaces

Vicinal surfaces with small misorientation angles exhibit a step array with a well-defined periodicity in the 10 nm range (32, 16 and 8 nm for 0.5° , 1° and 2° respectively). In the step flow growth mode, preferential absorption of growing species impinging on the terraces occurs at the step edges, leading to wire structures along the steps (fig. 2.1 (d)). Perpendicular to the in-wire direction, carriers are delocalised for short periods (8 nm), due to tunnelling through the lateral potential barriers, whereas they are confined in potential minima for larger periodicities (32 nm). This results in a red-shift of the optical transition energies and in the appearance of 1D subbands in the electronic structure. [Bloch 1994]. However, it is a major difficulty to fabricate misaligned substrates.

(d) Cleaved overgrown T-quantum wires

The process of the cleaved edge overgrowth method starts with the deposition of a specific multilayer structure on a GaAs (100) substrate typically in a molecular beam epitaxy (MBE) system [Pfeiffer 1988, Gershoni 1990, Wegscheider 1994]. Then the sample is removed from the growth chamber, moved into a neighbouring vacuum chamber and mechanically thinned from the backside and cleaned. After it is reloaded into the growth chamber and cleaved GaAs and AlGaAs layers are grown on the (110) cleaved plane immediately (fig. 2.1 (e)). The T-QWR concept was initially proposed by Störmer [Störmer] and Chang [Chang 1985] and experimentally demonstrated by Goni *et al.* [Goni 1992].

This two-step MBE technique accomplishes high-quality regrowth on the cleaved edge of a multilayer sample and is capable of producing quantum sized structures with atomic control in two directions [Pfeiffer 1990]. The lowest state wave function of these QWR structures is localized at the T-shaped intersection of the two GaAs QWs grown along the [001] and [110] direction, respectively. Near the T-intersection carrier confinement is somewhat relaxed leading to a smaller kinetic contribution to the total energy of both electrons and holes. A classical particle would be unbound at such an intersection, however, a quantum mechanical bound state forms with free-carrier motion limited to the line defined by the intersecting planes of the two QWs.

T-QWRs have exhibited high optical quality and the successful fabrication of an optically pumped laser based on such a structure has been reported by Pfeiffer *et al.* [1994].

(e) Modulation-doped quantum wires

To add free carriers into a QWR dopant atoms can simply be build into the corresponding QW layers. However, the ionised donors represent strong scattering centres for the carriers and result e.g. in poor mobilities and sometimes non-radiative recombination via impurity levels.

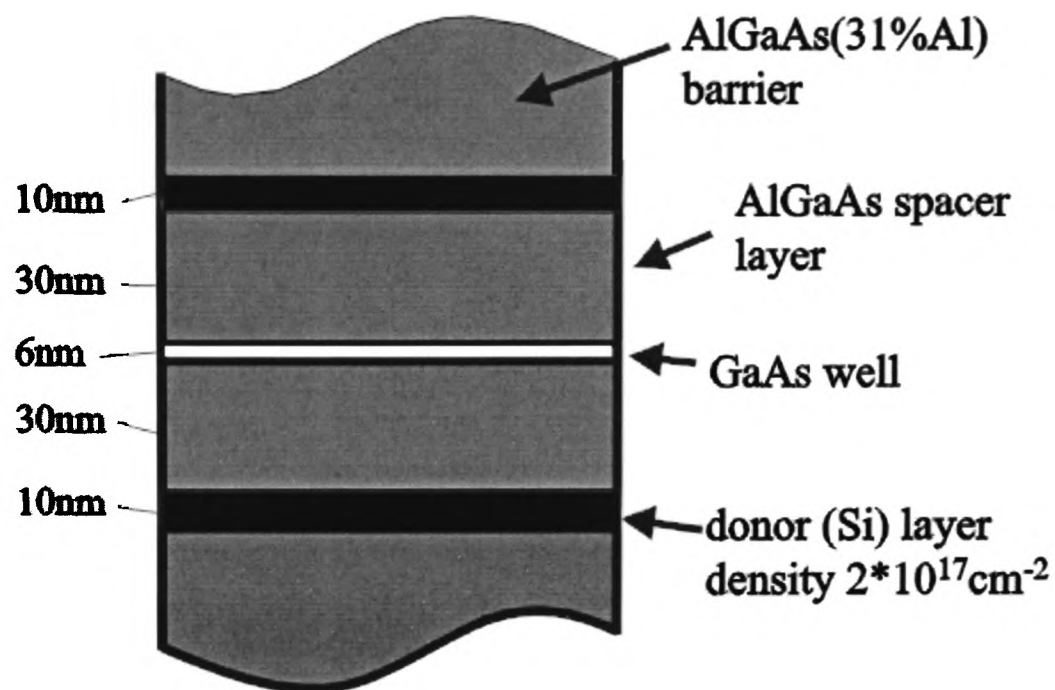


Figure 2.3: *Layer sequence of a modulation-doped quantum well.* The doping layer, which is separated from the quantum well by a spacer layer, introduces free carriers into the quantum well. The spatial separation of quantum well and doping layer decreases the scattering rate of the carriers with the doping ions. Such a growth sequence is used on a pre-patterned GaAs substrate to fabricate modulation-doped v-groove quantum wires.

Dingle and Störmer [1980] were the first to apply an alternative doping method to QWs which reduces the scattering probability significantly. Modulation-doping introduces the dopant atoms into a barrier layer separated by the QW or QWR by a spacer layer. In the case of the v-groove QWRs used for this work, the modulation-doping layer is typically 3 nm thick AlGaAs doped with silicon atoms at concentrations varying between $2 \times 10^{16} \text{ cm}^{-3}$ and $2 \times 10^{17} \text{ cm}^{-3}$. The doped layer is embedded in AlGaAs and is separated by 30 nm from the GaAs layer (fig. 2.3). The carriers ultimately escape by tunnel or thermoionic effect into the smaller band gap material GaAs and therefore increase the concentration of the electron gas in the QWR. The spatial separation of the electrons from the ionised dopant atoms leads to significantly decreased scattering rates.

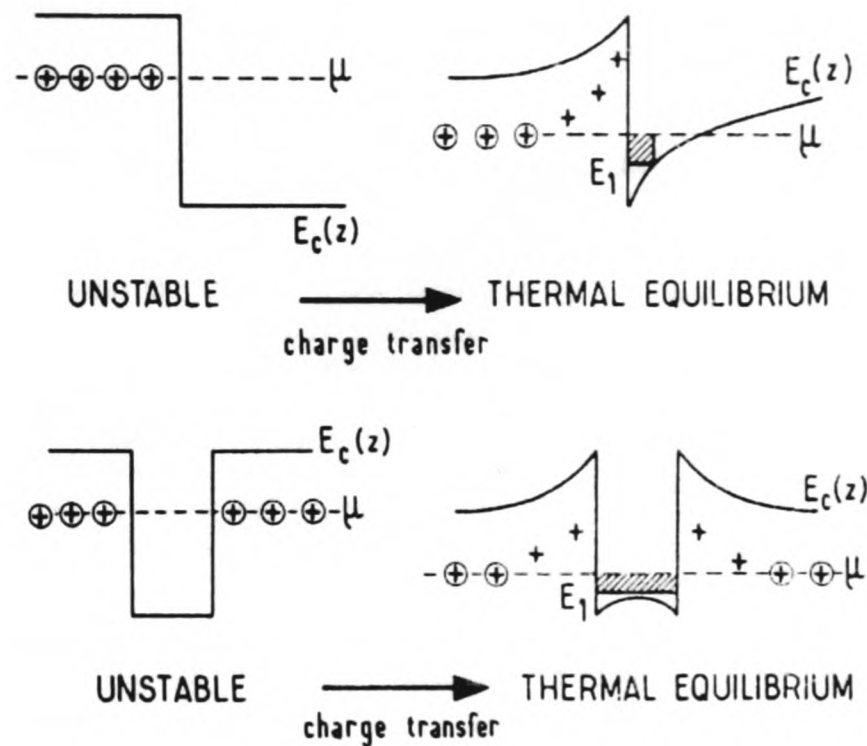


Figure 2.4: *Band bending in modulation-doped quantum wells.* To achieve a thermodynamic equilibrium in modulation-doped structures, the free carriers from the dopant atoms relax into the smaller band-gap material and leave behind charged ions. This induces an electric field and leads to a bending of the bands.

The positively charged dopant atoms left behind in the doping layer and the electrons in the QWR create an electric field, which leads to band-bending (fig. 2.4). The resulting potential profile felt by an electron is quasi-triangular near the interface.

2.3 CONDUCTION BAND IN ONE-DIMENSION

As mentioned in the introduction of this thesis a range of improved optical and electrical properties have been predicted in numerous publications. Mobilities are expected to increase in 1DEGs [Sakaki 1992, Motohisa 1992] and QWRs lasers exhibit lower threshold currents [Tiwari 1994]. Those theoretical results are based on the concept of energy subbands and

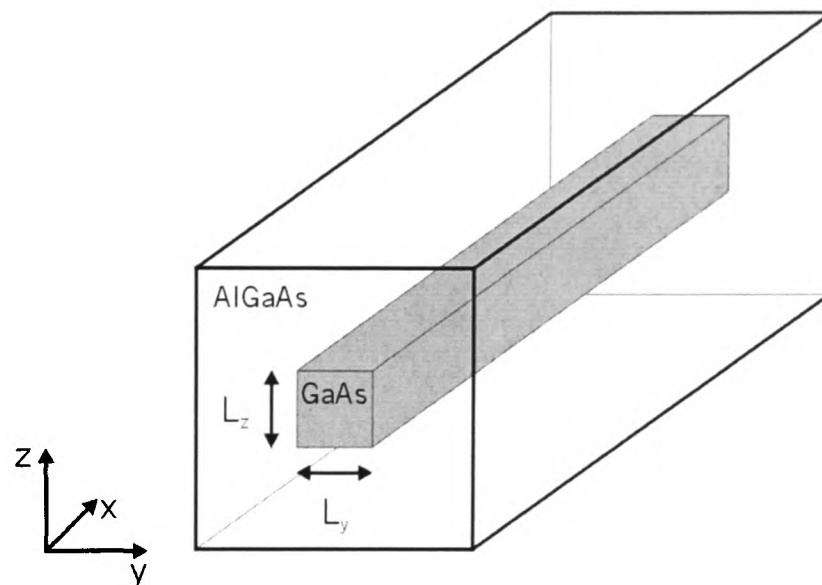


Figure 2.5: Diagram for model to calculate conduction bands in rectangular cross-section quantum wires. The GaAs quantum wire embedded in the barrier material AlGaAs is described by the lateral width L_y and the thickness L_z , where z is the growth direction and x the wire direction.

density of states, which distinguish zero from three dimensional electron gases fundamentally.

Consider a box with sides L_x , L_y and L_z and assume that there is zero potential energy for electrons inside and a finite potential outside (fig. 2.5). The potential step ΔE_C for both electrons and holes occurs at the heterointerfaces at $Y = \pm L_y/2$ and $Z = \pm L_z/2$.

The one-electron Schrödinger equation may be written as

$$\left[\frac{p_x^2 + p_y^2 + p_z^2}{2m_e} + V(y, z) \right] \psi^e(x, y, z) = E \psi^e(x, y, z) \quad (2.1)$$

and has analytic solutions satisfying the boundary condition $\psi^e_{xyz}(\mathbf{r}) = 0$

$$\psi^e(x, y, z) = \sqrt{\frac{8}{L_x L_y L_z}} \sin\left(\frac{l\pi x}{L_x}\right) \sin\left(\frac{m\pi y}{L_y}\right) \sin\left(\frac{n\pi z}{L_z}\right) \quad (2.2)$$

with energies

$$E = \frac{\hbar^2 \pi^2}{2m_e} \left[\left(\frac{l}{L_x}\right)^2 + \left(\frac{m}{L_y}\right)^2 + \left(\frac{n}{L_z}\right)^2 \right], \quad (2.3)$$

where l, n and $m = 1, 2, 3 \dots$. In bulk semiconductors, where the lengths L_i are on the scale of millimetres, the quantum numbers l, m and n become very large and the kinetic energy terms are very small in the scale of 10^{-10} meV. The energy levels

$$E = E(\mathbf{k}) = \frac{\hbar^2 \mathbf{k}^2}{2m_e} \quad (2.4)$$

with $\mathbf{k} = (l\pi/L_x, m\pi/L_y, n\pi/L_z)$ are quasi-continuous.

A strictly 1D structure, which is to be distinguished from the quasi 1D case, is only obtained, when L_y and L_z tend to zero. The energy in this ideal case is $(\hbar^2 \pi^2 / 2m_e)[(m/L_y)^2 + (n/L_z)^2]$. In practice, the solution of the one-electron Schrödinger equation is

$$\psi^e(x) = \sqrt{\frac{2}{L_x}} \sin\left(\frac{n\pi x}{L_x}\right), \quad (2.5)$$

with an energy

$$E_l = E_l(\mathbf{k}_x) = \frac{\hbar^2 \mathbf{k}_x^2}{2m_e}. \quad (2.6)$$

In the quasi 1D case, L_y and L_z are finite but small, typically in the order of nanometers. Since the potential does not depend on x , the wavefunction should be a plane wave along the x -direction, so that

$$\psi^e(x, y, z) = \frac{1}{\sqrt{L_x}} \Psi^e(y, z) \exp(ik_x x). \quad (2.7)$$

The envelope function $\Psi^e(x, y, z)$ now satisfies the 2D Schrödinger equation

$$\left[\frac{p_y^2 + p_z^2}{2m_e} + V(y, z) \right] \Psi^e_i(y, z) = E_i \Psi^e_i(y, z). \quad (2.8)$$

The potential is now a function of both y and z and therefore the envelope function may not in general be separable in y and z . Considerable simplification results if the barriers are assumed to have infinite height. Using $V_e = \infty$ at $y = \pm L_y/2$ and also $z = \pm L_z/2$, the envelope function can be expressed as

$$\Psi^e_i(y, z) = \frac{1}{\sqrt{L_y L_z}} \sum_{k_y, k_z} c(k_y, k_z) e^{i(k_y y + k_z z)}, \quad (2.9)$$

with expansion coefficients $c(k_y, k_z)$.

The energy levels are described by

$$\begin{aligned}
 E &= \frac{\hbar^2 \pi^2}{2m_e} \left[\left(\frac{l}{L_x} \right)^2 + \left(\frac{m}{L_y} \right)^2 + \left(\frac{n}{L_z} \right)^2 \right] \\
 &= E(k) = \frac{\hbar^2 k_x^2}{2m_e} + \frac{\hbar^2 \pi^2}{2m_e} \left[\left(\frac{m}{L_y} \right)^2 + \left(\frac{n}{L_z} \right)^2 \right].
 \end{aligned} \tag{2.10}$$

The energy levels are quasi-continuous in the x -direction and are discrete and separated by the confinement in the other two directions. Energy levels in quasi-dimensional systems, which vary like $\hbar^2 k^2 / 2m_e$ and start off from discrete energies at $k = 0$ form so called subbands (fig. 2.6).

Analogous dispersion relations can be derived for hole energies, if the electron mass is replaced with the light hole and the heavy hole masses. This leads to a separation of the light hole and heavy hole valence bands. However, a more accurate calculation of realistic bands is complicated and requires more sophisticated methods which will be explained in the following chapter.

The density of states (DOS) can now be derived by applying periodic boundary conditions along the x -axis. The DOS for subband i can be written as

$$n_i(E) = n_i(k_x) 2 \left(\frac{dE}{dk_x} \right)^{-1} = \frac{g_s L_x}{\pi \hbar} \left\{ \frac{m_e}{2(E - E_i)} \right\}^{1/2} \tag{2.11}$$

where g_s is the spin degeneracy. A factor of 2 has been included to account for both $+$ and $-k_x$. As it can be seen in fig. 2.6, the DOS for the Q1D case shows singularities at the subband edges E_i .

In quasi 0D structures the totally discrete energy solutions give sharp energy levels of the form of $\delta(E - E_i)$. For quasi 1D systems each lateral discrete solution of Schrödinger equation results in a separate $1/\sqrt{E}$ -branch. The DOS for all dimensions are shown in fig. 2.6, while fig. 2.7 shows the influence of inhomogeneous broadening on the DOS in 1D.

The number of electrons N_i per subband per unit length at 0 K can now be calculated as

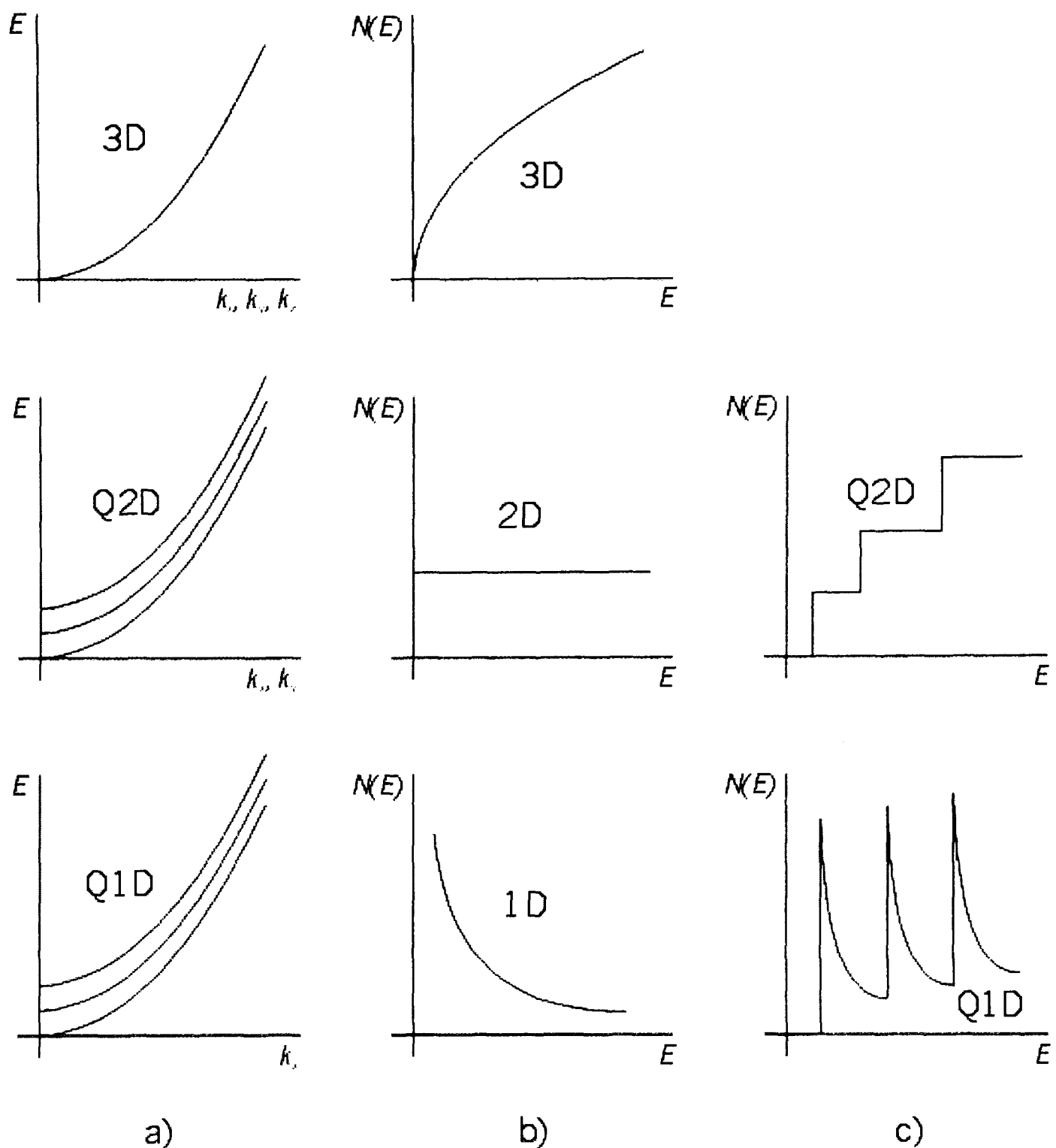


Figure 2.6: Energy bands and density of states in various dimensions. While in bulk (3D) only one energy band can be found in the conduction band, in quasi-one (Q1D) and quasi-two dimensional (Q2D) semiconductor structures subbands occur due to quantum confinement. In the Q1D case the subbands exist in the wire direction and the density of states exhibit singularities at each energy level.

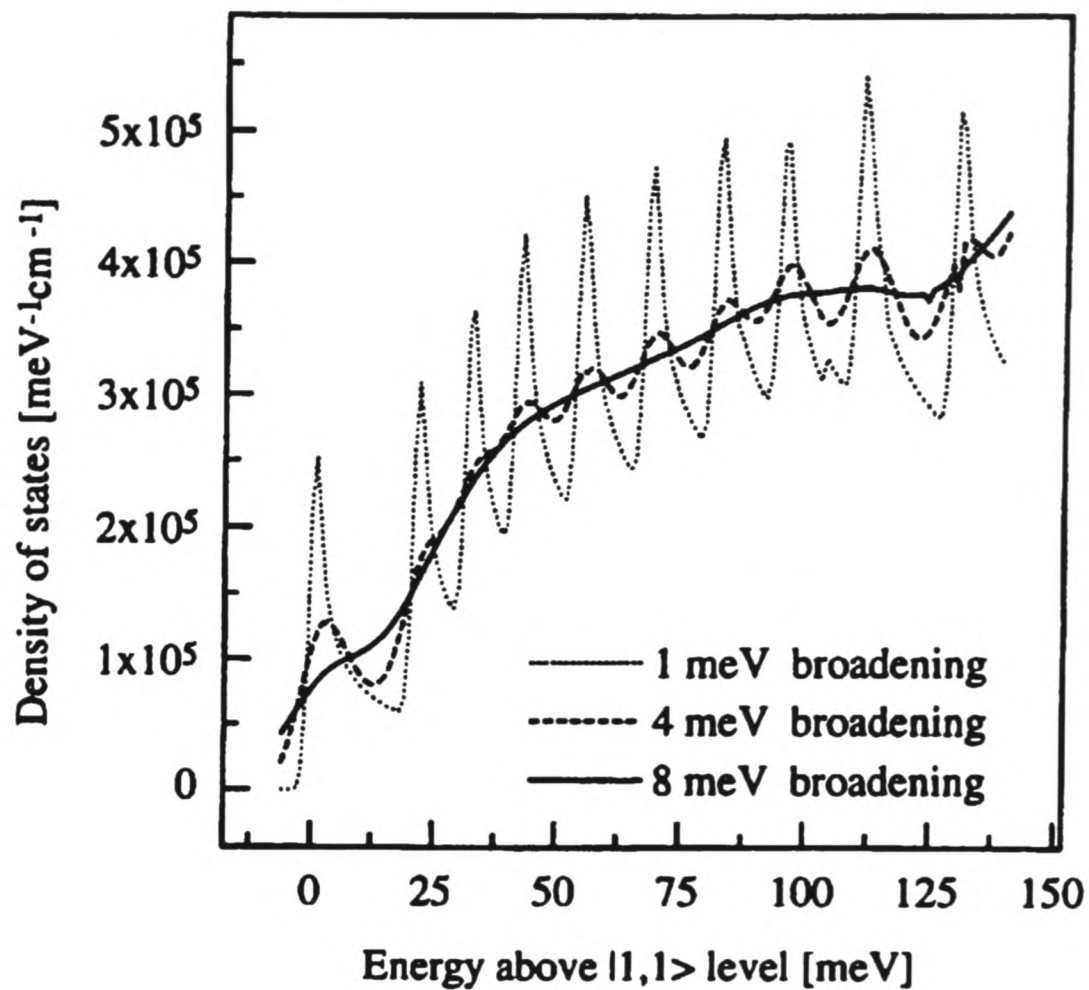


Figure 2.7: Calculated 1D electron density of states with different degrees of inhomogeneous broadening.

$$N_i = g_s \int_{E_i}^{E_F} n_i(E) dE = \frac{g_s^2 L_x}{\pi \hbar} \sqrt{2m_e(E_F - E_i)}, \quad (2.12)$$

where E_F is the Fermi level.

2.4 VALENCE BAND AND INTERBAND OPTICAL TRANSITIONS

The theoretical models of the 1D conduction band predict effects largely similar to that in 2D QWs, i.e. quantization of subbands due to quantum confinement. Studies of the nature of the valence band have revealed features unique to the 1D system. Unlike the case of QWs, the quantum confinement in two spatial directions gives rise to valence band mixing at the centre of the Brillouin zone. The mixing of the heavy hole (hh) and the light hole (lh) states,

which can be tuned by the lateral confinement potential, leads to modified energies of the optical interband transitions and to a redistribution of the oscillator strength. Moreover, the modified valence-band structure results in intrinsic polarization anisotropy, as it will be presented later in this chapter.

A series of valence band calculations have been published to date. Apart from an effective orbital-bond model [Citrin 1991], most of them are based on coupled band models [Sercel 1990, 1991, Vouilloz 1997, 1998]. An outline of the coupled band model by Bockelmann is given in the following [Bockelmann 1991]. In the following the x -axis describes the wire direction, while the carriers are confined in y and z , the lateral and growth directions in a rectangular QW.

The model derives an analytical solution for the calculation of optical transitions near the fundamental absorption edge. Therefore, the conduction band can be treated in the single-band effective-mass approximation. Similarly to the construction of envelope wavefunctions in chapter 2.3

$$\Psi^e = \sqrt{\frac{2}{L_x L_y}} \sin\left(\frac{n^e \pi y}{L_y}\right) \exp(ik_x x) \chi_e(z). \quad (2.13)$$

L_y and n^e are the lateral wire width and subband index respectively. χ_e stands for the ground-state wavefunction in the z -direction.

In the valence band two different carrier types have to be taken into account, the heavy and the light holes. The valence subbands dispersions are assumed to be non-parabolic [Brum 1988, Sweeny 1988, Citrin 1989] and the wave functions are constructed with the three lower band edge eigenstates of the QW in the z -direction.

$$\Psi^h = \sqrt{\frac{2}{L_x L_y}} \sum_{n=1}^{\infty} \left(g_n \chi_{h1}(z) \left| \frac{3}{2} \right\rangle h_n \chi_{l1}(z) \left| -\frac{1}{2} \right\rangle l_n \chi_{h2}(z) \left| -\frac{3}{2} \right\rangle \right) \sin\left(\frac{n^e \pi y}{L_y}\right) \exp(ik_x x) \quad (2.14)$$

χ_{h1} , χ_{h2} and χ_{l1} indicate the envelope functions of the first, the second hh and the first lh, respectively. The kets represent the periodic parts of the Bloch functions labelled by the z -

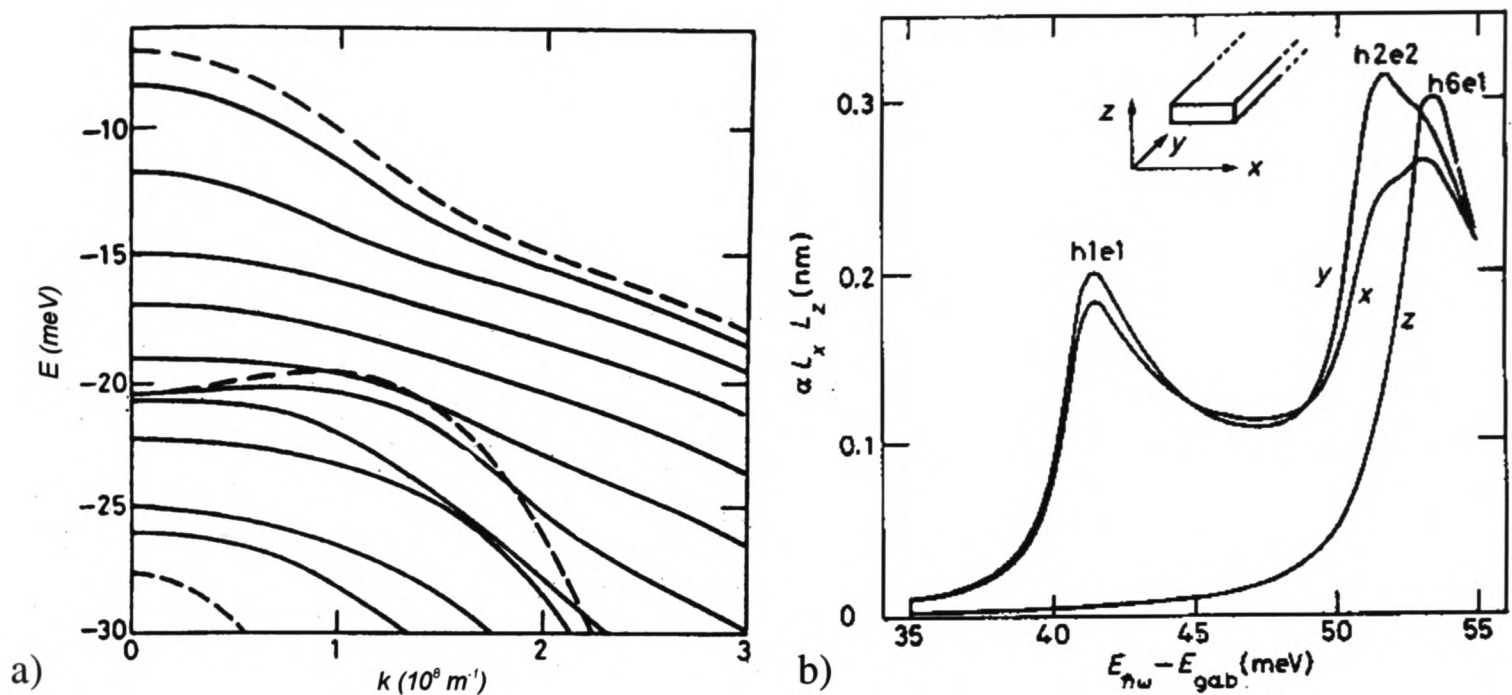


Figure 2.8: *Valence band calculations* [Bockelmann 1991] (a) Calculated valence subband energies of a quantum wire (solid line) with a $50 \times 10 \text{ nm}^2$ cross-section as a function of the in-wire wavevector and of the corresponding 10 nm thick quantum well (dashed line) as a function of the in-plane wavevector. The top of the bulk GaAs valence band corresponds to energy $E = 0 \text{ meV}$. (b) Absorption spectra plotted for three orthogonal light polarisations. The sixth hole state (h6) is close to the light hole band in the quantum well and has a dominating light hole character.

component of the (pseudo) angular momentum J . Due to the inversion symmetry the set $\chi_{h1}(z)|-\frac{3}{2}\rangle, \chi_{l1}(z)|\frac{1}{2}\rangle, \chi_{h2}(z)|-\frac{3}{2}\rangle$ is not needed in the wavefunction expansion.

In the next step the Luttinger-Kohn Hamiltonian [Luttinger 1955] is applied in the axial approximation [Altarelli 1986] resulting in an eigenvalue matrix which has to be diagonalized numerically. After the eigenvectors and eigenvalues for lh and hh are calculated, the lh and hh eigenstates can be superimposed to form QWR eigenstates. The resulting valence band dispersions are shown in fig. 2.8 (a) for a QWR with a $50 \times 10 \text{ nm}^2$ cross-section. The coupling of eigenstates in the valence band due to the lateral confinement introduces contributions of hh and lh character to each valence subband, even at $k = 0$. Nevertheless, single valence band states can be dominated by one carrier type. For example

the first and the sixth subband are similar to the 2D hh1 and lh1 bands. The mixing gives rise to non-parabolic dispersion curves and anticrossings of the subbands.

In the electric dipole approximation the absorption coefficient is given to first order of perturbation theory by [Bastard 1986, Kane 1957]:

$$\alpha = \frac{4\pi^2 e^2}{n c m_0^2 \omega V} \sum_{i,f} |\langle f | \epsilon | i \rangle|^2 \delta(E_f - E_i - \hbar\omega), \quad (2.15)$$

where m_0 , n , V , ω , and ϵ indicate the free-electron mass, refractive index, sample volume, light frequency and polarization (electric-field) vector, respectively.

It is assumed that any initial state i (final state f) is occupied (unoccupied). For 1D interband transitions the matrix element in equation (2.15) is

$$|\langle f | \epsilon \mathbf{p} | i \rangle|^2 = 2 \sum_{\sigma=\uparrow,\downarrow} \left| \langle s_\sigma | \epsilon \mathbf{p} | \frac{3}{2} \rangle J_{h1} + \langle s_\sigma | \epsilon \mathbf{p} | -\frac{1}{2} \rangle J_{l1} \right|^2 \quad (2.16)$$

The factor 2 accounts for the Kramer's degeneracy of the valence band. The sum extends over the spin-up and spin-down atomic wave functions of the conduction band. J_{h1} and J_{l1} are the overlap integrals of the electron and hole envelope functions:

$$\begin{aligned} J_{h1} &= g_n e \int dz \chi_e^*(z) \chi_{h1}(z) \\ J_{l1} &= h_n e \int dz \chi_e^*(z) \chi_{l1}(z). \end{aligned} \quad (2.17)$$

χ_e and χ_{h2} have opposite parity, hence J_{h2} equals zero and does not appear in equation (2.16).

Evaluating the atomic-like matrix elements yields [Bockelmann 1991]

$$|\langle f | \epsilon \mathbf{p} | i \rangle|^2 = \left(\frac{m_0 P}{\hbar} \right)^2 \left\{ \left(J_{h1}^2 - \frac{2 J_{h1} J_{l1}}{\sqrt{3} \cos(2\varphi)} + \frac{J_{l1}^2}{3} \right) \sin^2(\vartheta) + \frac{4}{3} J_{l1}^2 \cos^2(\vartheta) \right\}, \quad (2.18)$$

where P is the Kane matrix element [Kane 1957]. Here, the polarization vector ϵ is expressed by the azimuthal angle ϑ (measured from z) and the polar angle φ (measured from x) in ordinary spherical coordinates.

The calculated absorption spectra are shown in fig. 2.8 (b) for a polarisation vector parallel to the x , y and z axis. The peaks are broadened by Lorentzian functions with a full width at half maximum of 2 meV, simulating a broadening effect in a real experiment. The spectra

reveal a polarisation anisotropy of the absorption intensities due to the valence band mixing, unique to 1D structures.

The polarisation anisotropy for x and y depends on the sign of J_{hl} and J_{ll} in (2.18); if they are of equal (opposite) sign the absorption is weaker for x - (y -) polarisation. As the hh-lh mixing increases the product of J_{hl} and J_{ll} increases and the anisotropy becomes stronger. The absorption in z -direction is dominated by the $h6e1$ transition (from the sixth hole band to the first electronic level). hh atomic functions are forbidden for the z -polarisation and the valence band wave functions exhibit strong lh contributions. Calculations of the x - y anisotropy as a function of the wire width L_x show that with increasing wire width the polarisation anisotropy decreases due to weaker hh-lh mixing. Independent of the wire width is the fact that the only important transitions are $h1e1$, $h2e2$ and the ones involving valence subbands with strong lh-character, near the $lh1$ energy of a QW in fig. 2.8 (a).

However, it should be noted that polarisation anisotropy in optical spectra can be due to a number of reasons as physical effects (e.g. strain, uniaxial stress), anisotropic interface roughness or electromagnetic effects due to surface corrugation [Kajikawa 1993].

2.5 BANDSTRUCTURE CALCULATIONS

Theoretical models for v-groove QWR bandstructures have been developed to predict or interpret transition energies in optical spectra. The typically few nm thick GaAs-layer on the bottom of the V-groove has an abrupt transition to the barrier material in the growth direction which provides confinement in 1D. Confinement in the lateral direction, however, is given only by the tapering thickness of the GaAs-layer. Due to the relatively complicated form of the wire the analytical solutions even for quasi-1D-systems [Anthony 1994, Kelly 1995], with rectangular or circular wires are not adequate. The first theoretical model introduced in the following describes the crescent shape of the v-groove QWR in the

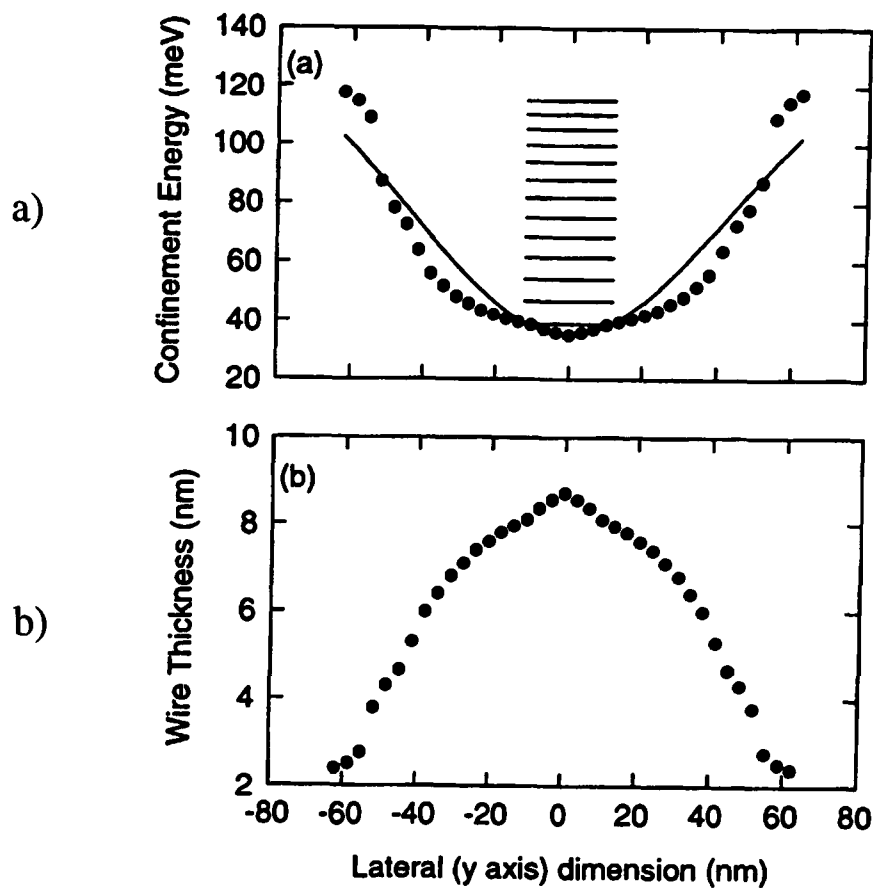


Figure 2.9: *Confinement energies as function of lateral position in the wire* (Turner 1995). (a) The confinement energies (solid circles) are shown for electrons in the lowest subband at different positions in the wire. The analytic eigenvalues are indicated by the horizontal lines, while the line is a $\tanh^2$ -curve fit by a least squares method. (b) The used wire thicknesses are shown as a function of the lateral position in the wire.

framework of perturbation theory, while the plane-wave QWR bandstructure calculation actually uses a cross-section picture of a QWR structure as an input for the numerical simulation.

(a) Perturbation theory approach

The main difficulty to theoretically describing optical transitions in v-groove QWRs is the complexity of the wire geometry. The crescent shape of v-groove QWRs can be taken into account by using perturbation theory resulting in a simple analytical equation (fig. 2.9).

In this theoretical approach the lateral gradual variation of the QWR in a v-groove is described as a 2D-QW with a perturbation [Kapon 1989]. The lowest QW levels are

calculated in the effective-mass approximation using a finite-well model in dependence of the lateral dimension y . The resulting lateral potential profile is approximated by

$$U(y) = E_{\text{el}}(0) + \Delta E \tanh^2(y/2W), \quad (2.19)$$

where $E_{\text{el}}(0)$ is the confinement energy at the centre of the crescent, $\Delta E \equiv E_{\text{el}}(\infty) - E_{\text{el}}(0)$ ($E_{\text{el}}(\infty)$: effective conduction-band edge far away from the centre) and W a measure of the potential well width. The energy levels of (2.19), measured from the band edge of the bulk material, are given by Landau *et al.* [1977]:

$$E_{\text{el},m} = E_{\text{el}}(0) + \Delta E - \frac{\hbar^2}{2m^*W^2} \left[-(1+2m) + \sqrt{1 + \frac{2m^*W^2\Delta E}{\hbar^2}} \right]^2 \quad (2.20)$$

$$, m = 0, 1, \dots,$$

where m^* is the effective mass of the electrons. Equation (2.20) shows that the gradually varying thickness of the QWR creates subbands as a perturbation, starting at discrete energy levels $E_n(0)$. The model has limits, e.g., it does not consider the v-shaped bending of the QWR, but it can help to estimate optical transitions in the v-groove QWR.

(b) Plane-wave QWR bandstructure calculation

To run simulations which yield more accurate predictions for optical transitions than in the previous models, the integration of the real shape of the v-groove QWR would be ideal, eliminating artefacts due to an unrealistic wire geometry. For that purpose, a self-consistent Poisson-Schrödinger solver was developed by Eoin O'Sullivan [O'Sullivan 2000], which was used in conjunction with the experimental results presented in this thesis. This numerical simulation uses the actual shape of the QWR taken from a cross-section transmission electron micrograph (TEM) (fig. 2.10) as an input parameter.

As shown in chapter 2.2 the single particle Schrödinger equation for the 2D potential $V(y, z)$ is

$$\left[\frac{p_y^2 + p_z^2}{2m_e} + V(y, z) \right] \Psi^e_i(y, z) = E_i \Psi^e_i(y, z), \quad (2.21)$$

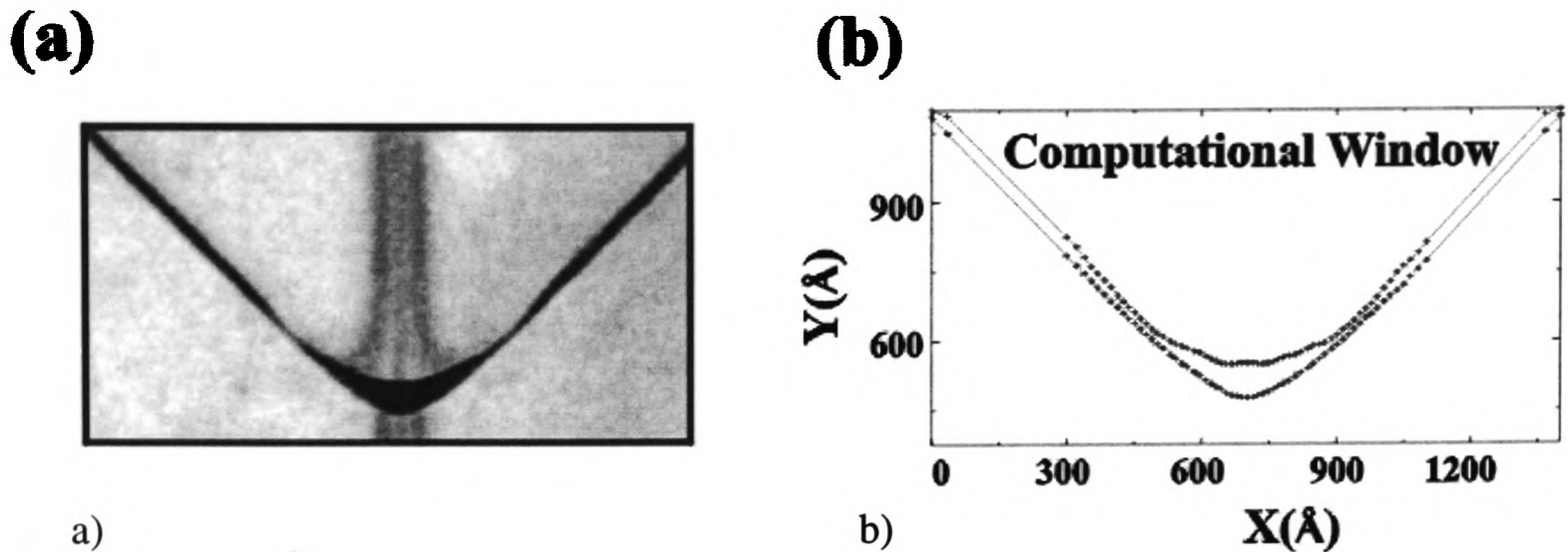


Figure 2.10: *Extraction of the wire shape from transmission electron microscopy (TEM) picture for the Poisson-Schrödinger simulation. (a) The TEM picture on the left shows the quantum wire region including parts of the side quantum well and the vertical quantum well. (b) The shape of the structure was reconstructed graphically for experimentally investigated samples and used as input information for the simulation to calculate the energy levels.*

the corresponding subbands

$$E_l = E_l(\mathbf{k}_x) = \frac{\hbar^2 \mathbf{k}_x^2}{2m_e} \quad (2.22)$$

and the carrier wavefunctions can be described as

$$\psi^e(x, y, z) = \frac{1}{\sqrt{L_x}} \Psi^e(y, z) e^{i(k_x x)}. \quad (2.23)$$

The envelope function can be written as

$$\Psi^e_i(y, z) = \frac{1}{\sqrt{L_y L_z}} \sum_{k_y, k_z} c(k_y, k_z) e^{i(k_y y + k_z z)} \quad (2.24)$$

and to calculate the Schrödinger equation numerically, it can be transformed into a matrix equation in the plane wave basis:

$$\sum_{k'_y, k'_z} \left(\frac{\hbar^2 (k_y^2 + k_z^2)}{2m^*} \delta_{k'_y, k'_z, k_y, k_z} + V(k'_y, k'_z; k_y, k_z) - E_l \delta_{k_y, k'_y, k_z, k'_z} \right) c(k'_y, k'_z) = 0, \quad (2.25)$$

where $V(k'_y, k'_z; k_y, k_z)$ are the matrix elements of the 2D confinement potential $V(y, z)$ in the plane wave basis

$$V(k'_y, k'_z; k_y, k_z) = \frac{1}{L_y L_z} \iint e^{i(k'_y y + k'_z z)} V(y, z) e^{i(k_y y + k_z z)} dy dz. \quad (2.26)$$

The Schrödinger equation (2.26) can now be solved for undoped v-groove QWRs, using standard matrix diagonalization techniques [Numerical Algorithm Group 1983].

To calculate the bandstructure of doped QWRs the electric field induced by dopant ions and the added carriers have to be taken into account. Therefore, a Poisson solver has been included in the simulation and the electrostatic potential is calculated self-consistently.

The Poisson equation for a 2D electrostatic potential is

$$\frac{\partial}{\partial x} \epsilon(x) \frac{\partial}{\partial x} \phi(x) + \frac{\partial}{\partial y} \epsilon(x, y) \frac{\partial}{\partial y} \phi(x, y) = \lambda \left| \frac{\Psi_i(x, y)}{\sqrt{L_x L_y}} \right|^2, \quad (2.27)$$

where $\epsilon(x)$ is the material dependent dielectric function and λ is the linear charge density. A

Fourier transformation yields

$$\sum_{k_{yi}, k_{zi}} \left[(k_{yi} k_{yj} + k_{zi} k_{zj}) \epsilon(k_{yi} k_{zi}; k_{yj} k_{zj}) \right] \phi(k_{yj} k_{zj}) = -\frac{e}{\epsilon_0} \rho(k_{yj} k_{zj}). \quad (2.28)$$

Before the Poisson equation can be solved the charge density $\rho(k_{yj} k_{zj})$ has to be determined.

While in the case of a 2D QW the values can be obtained analytically, the density of states for the 1D case $n(E) \propto 1/\sqrt{E}$ is energy-dependent and prevents a straightforward solution.

The charge density has to be derived from the number of occupied subbands and the Fermi level, which can be determined in a self-consistent iterative process [O'Sullivan 2000]. Then the charge density is calculated and inserted into the Poisson equation which yields the electrostatic potential.

A calculation with a self-consistent Schrödinger-Poisson simulation starts with the solution of the Schrödinger equation for an undoped QWR, which outputs the wavefunction distribution $\psi^e(x, y, z)$. The wavefunctions are then inserted in the Poisson equation. The

solution of the Poisson equation results in an electrostatic potential, which changes the Schrödinger equation to

$$\sum_{k'_y, k'_z} \left(\frac{\hbar(k_y^2 + k_z^2)}{2m^*} \delta_{k'_y, k'_z, k_y, k_z} + V(k'_y, k'_z; k_y, k_z) + \Phi(k'_y, k'_z; k_y, k_z) - E_l \delta_{k_y, k'_y, k_z, k'_z} \right) c(k'_y, k'_z) = 0. \quad (2.29)$$

The refined Schrödinger equation is then solved and the cycle starts over again. The solutions converge after a certain number of iterations.

As mentioned earlier the simulations have been used to help the understanding of experimental results, directly by calculating the states for actual samples as well as indirectly by looking at idealized wires. These idealized wires are geometrical simplifications of a real v-groove QWR structure, but include all major features and have the dimensions of typical samples. The electron states were calculated as a function of several important parameters such as wire depth (length of horizontal barrier interface capping the wire region), degree of pinch-off between the SQW and QWR, length of SQW and carrier density to investigate their significance and influence on the 1D optical properties.

Fig. 2.11 shows the role of carrier densities on the energy states in a QWR which is about 30 nm wide and 20 nm thick. The length of the SQW is much shorter than in real structures, but calculations with longer SQWs, using the same number of planewaves, have shown that the results become less accurate due to a poorer description of the QWR. A computer with more processor power which is able to cope with a higher number of planewaves in a reasonable time could help to resolve this problem. The undoped wire in part (a) of fig. 2.11 exhibits five QWR states and a sixth electron state in the SQW. As the states become squeezed in the QWR, either by making the wire depth narrower or increasing the pinch-off between the SQW and the QWR, the higher QWR energy states can be moved into the SQW. Similarly, when the charge density is increased, e.g. to a linear charge density of $\lambda = 1 \times 10^8 \text{ m}^{-1}$ (fig. 2.11 (b)), less states are found in the QWR. In the given example, only

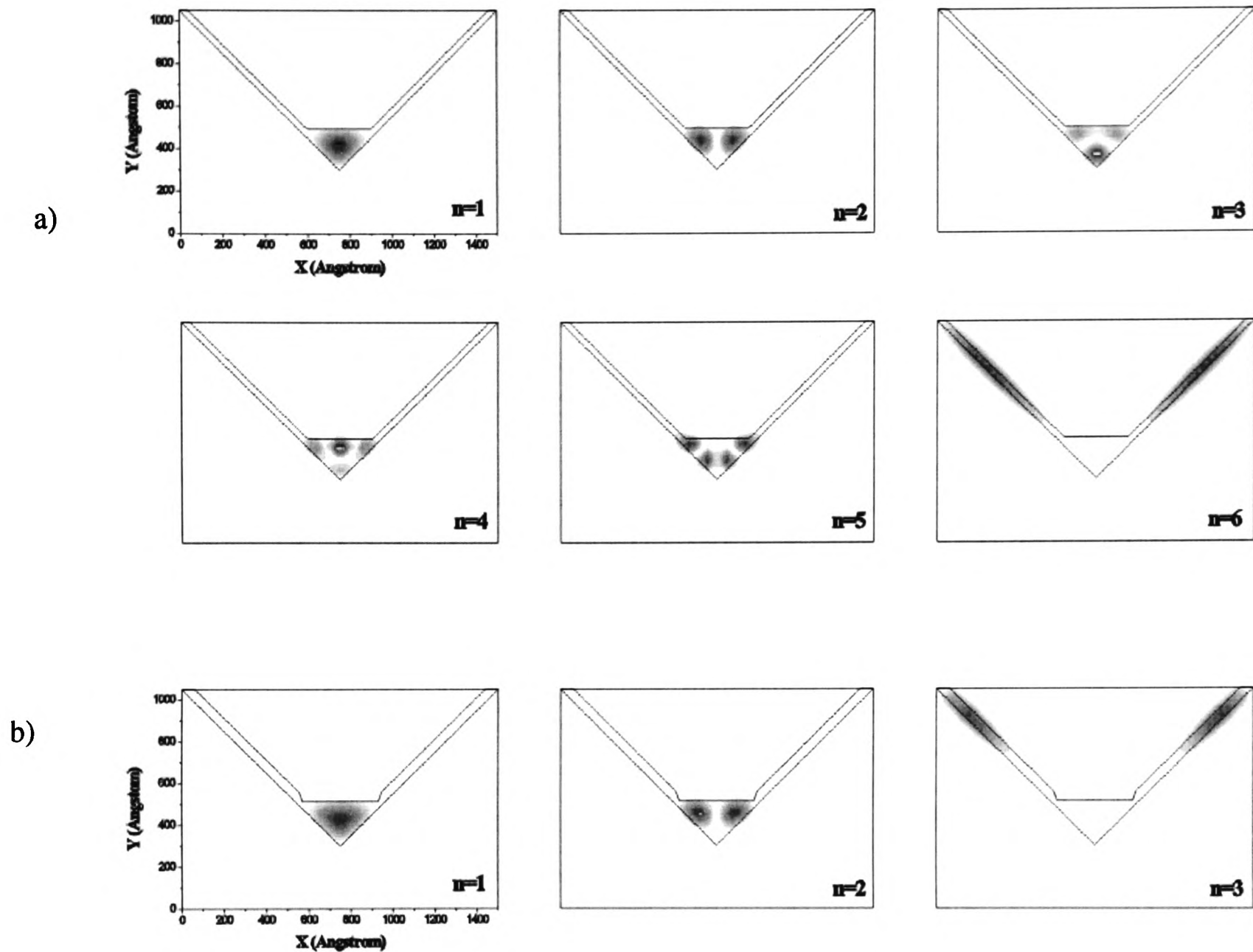


Figure 2.11: Results of the Poisson-Schroedinger simulation for ideal undoped and doped v-groove quantum wires. (a) The calculations for an ideal undoped quantum wire with typical dimensions (wire width: 30 nm, wire thickness: 20 nm) yield five quantum wire states and a sixth state in the side quantum wells. (b) For a comparable doped structure only the first two levels are found in the quantum wire due to increased carrier densities, while the third one already resides in the side quantum wells.

the first two electron states are 1D states. However, the small pinch-off of the doped sample slightly contributes to the shift of the states from the QWR into the SQW.

CHAPTER 3

FABRICATION OF V-GROOVE QUANTUM WIRES

CONTENTS

3.1	INTRODUCTION.....	32
3.2	PRE-PATTERNING.....	32
3.3	MOCVD GROWTH	36
3.4	METALLIZATION.....	38
3.5	STRUCTURAL ANALYSIS	39

3.1 INTRODUCTION

v-groove quantum wires are self-organised structures, grown on non-planar substrates. In photolithography and etch processes, a GaAs wafer is patterned with v-grooves and subsequently over-grown in a metal organic chemical vapour deposition (MOCVD) system with a sequence of GaAs, AlGaAs, doping and capping layers. The fabrication process demands a great deal of precision due to the small dimensions of the structures. It also requires very careful and clean handling, as the processing is done before the epitaxial growth and the quality of the grown semiconductor layers depend heavily on the pre-patterning. The successful fabrication of the numerous samples investigated in this work was done in collaboration with a research group at the Institute for Thin Film and Ion Technology, Jülich Germany, namely Andreas Kaluza and Axel Schwarz.

3.2 PRE-PATTERNING

The starting-material for the fabrication is a semi-insulating 2'' (100) GaAs substrate with exact surface orientation (0° off). Unless the substrate is so-called “epi-ready” it is cleaned from organic contamination in concentrated H_2SO_4 . A SiO_2 -layer is then deposited by plasma enhanced chemical vapour deposition with a slow growth rate to minimise the density of defects. In the following step the SiO_2 -layer is structured in a combined photolithographical and etching process and used as an etch mask to structure the v-grooves (fig. 3.1).

For a typical photolithographical process, the wafer is first cleaned in an ultrasonic bath with acetone and then with propanol. Afterwards an adhesion promoter (HMDS) is centrifuged onto the wafer to improve the adhesion of the photoresist on the SiO_2 . The photoresist is then spun onto the wafer and dried on a hot plate.

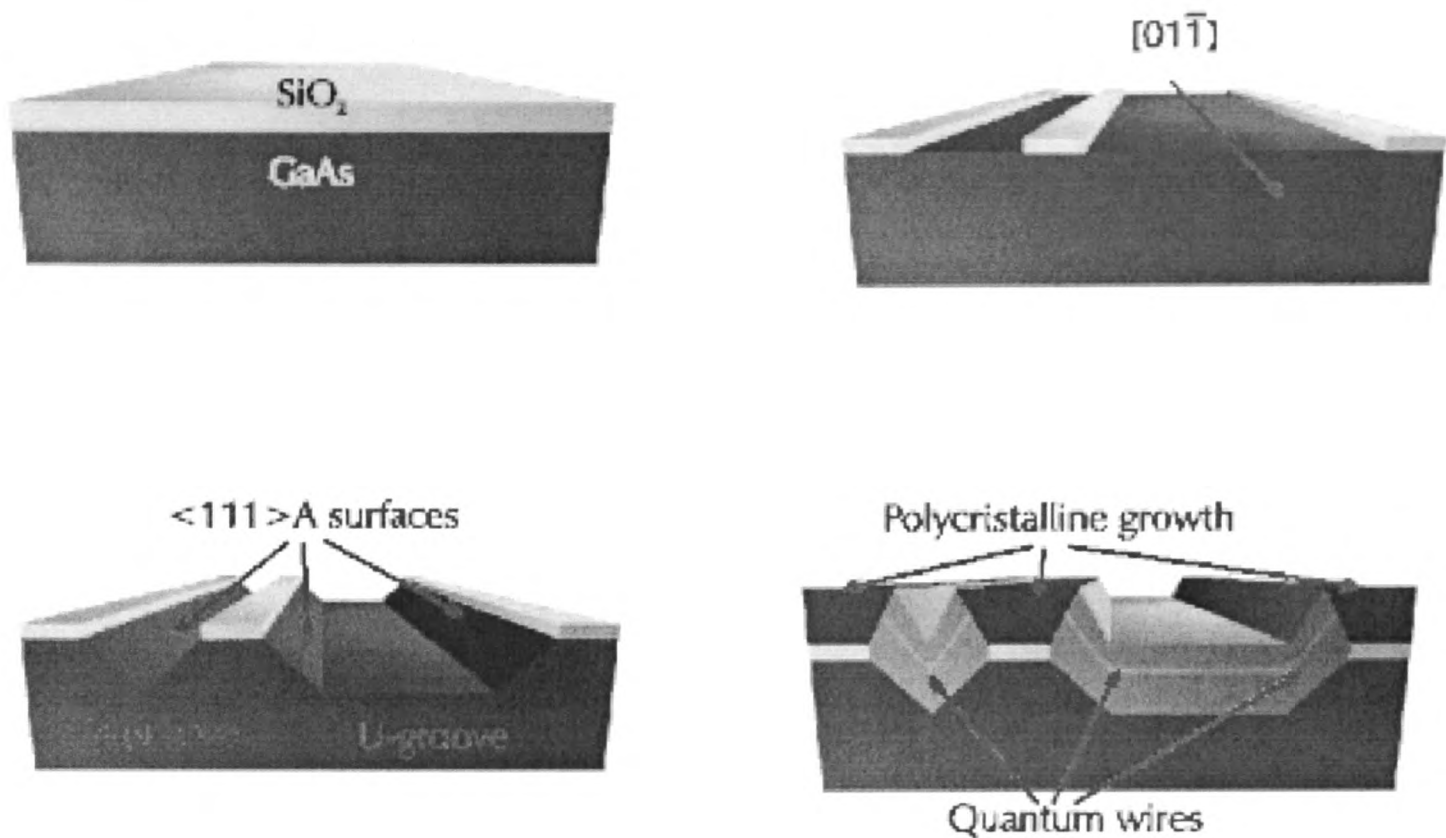


Figure 3.1: *Fabrication of v- and u-groove quantum wires.* (a) First a (100) GaAs substrate is covered with 30 nm SiO₂. (b) After a photolithographical process the SiO₂ layer is chemically etched so that stripes of GaAs substrate are exposed with apertures of 0.5 to 10 nm. (c) The exposure of the sample to AF91 results in v- or u-grooves, depending on the aperture of the SiO₂ openings. (d) In an MOCVD system GaAs quantum wires are grown, embedded in AlGaAs.

For the next step, the exposure of the photoresist, chrome masks were designed under AutoCAD. The set of masks consists of several layers of photolithographical patterns and contains structures for electrical (called electrical samples) and optical experiments (optical samples). While the electrical samples are complicated and feature a series of single wires (fig. 3.2), the areas for the optical samples contain hundreds of closely packed parallel wires. A typical optical sample is 5 x 5 mm and has about 500 parallel wires (fig. 3.3). The wire area is surrounded by a planar etched frame of 1-2 mm, called the off-wire region, which

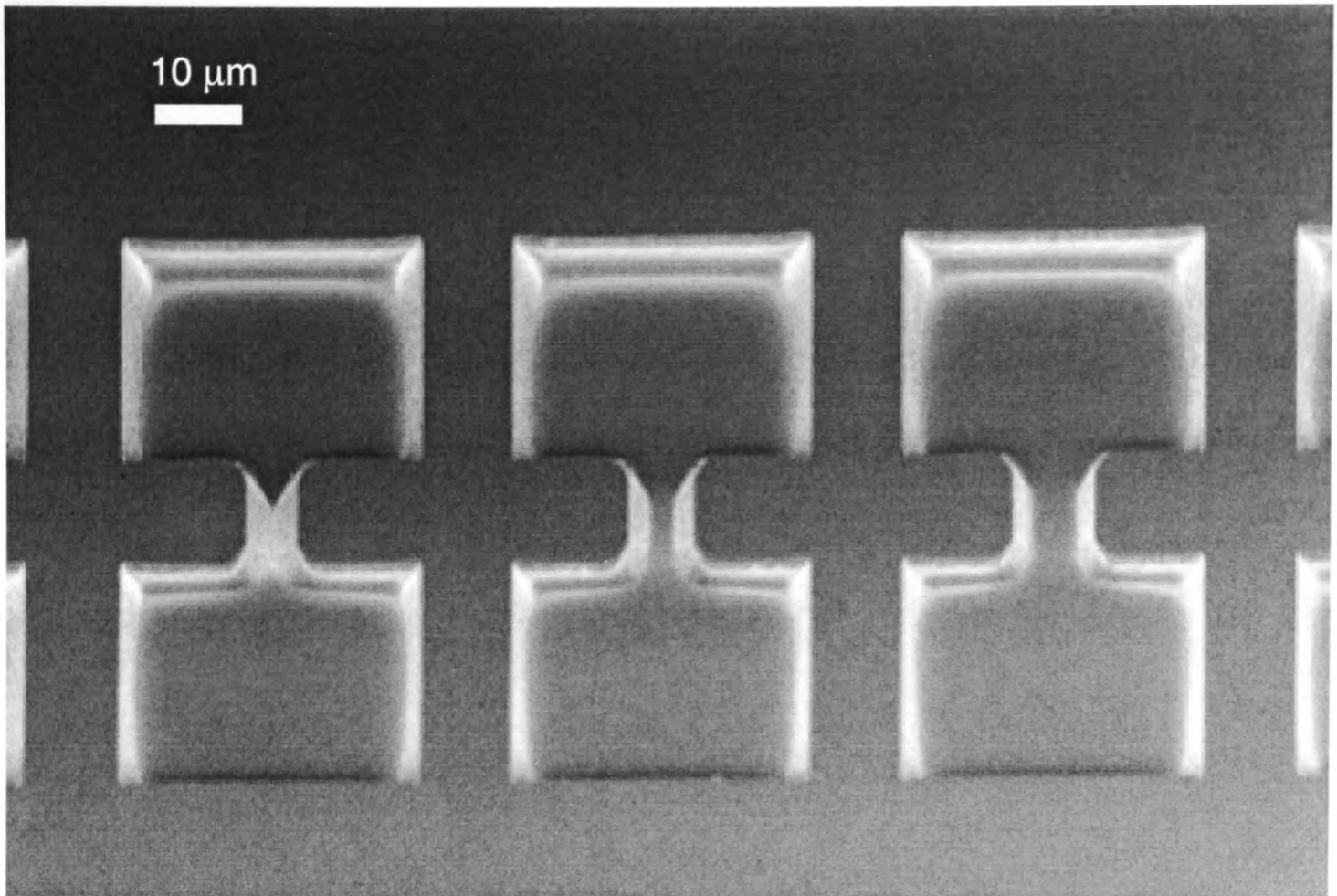


Figure 3.2: *Scanning electron microscopy picture of electrical sample before epitaxial growth.* The large squares represent contact pads. In between a pair of pads short v- and u- grooves of different width can be seen.

after the growth forms a quantum well (QW). The QW in the off-wire region is used as a reference to investigate the quality of the grown structure and to compare its optical properties with the ones of the SQW.

There are samples of different v-groove apertures on one quarter wafer, ranging from 0.5 – 10 μm and are separated by spacings of 1 μm or more. The different sizes produce either v-grooves with different SQW lengths or so-called u-grooves with quantum wells of different widths on the bottom of the u-groove. The structures are repeated on each of the wafer quarter, so that up to four different growth processes can be done from one wafer.

The wafer is placed in the mask aligner MA6 (Karl Süss) together with the chrome mask and is exposed to 436 nm uv-light in the hard-contact mode. It is essential that the wafer is

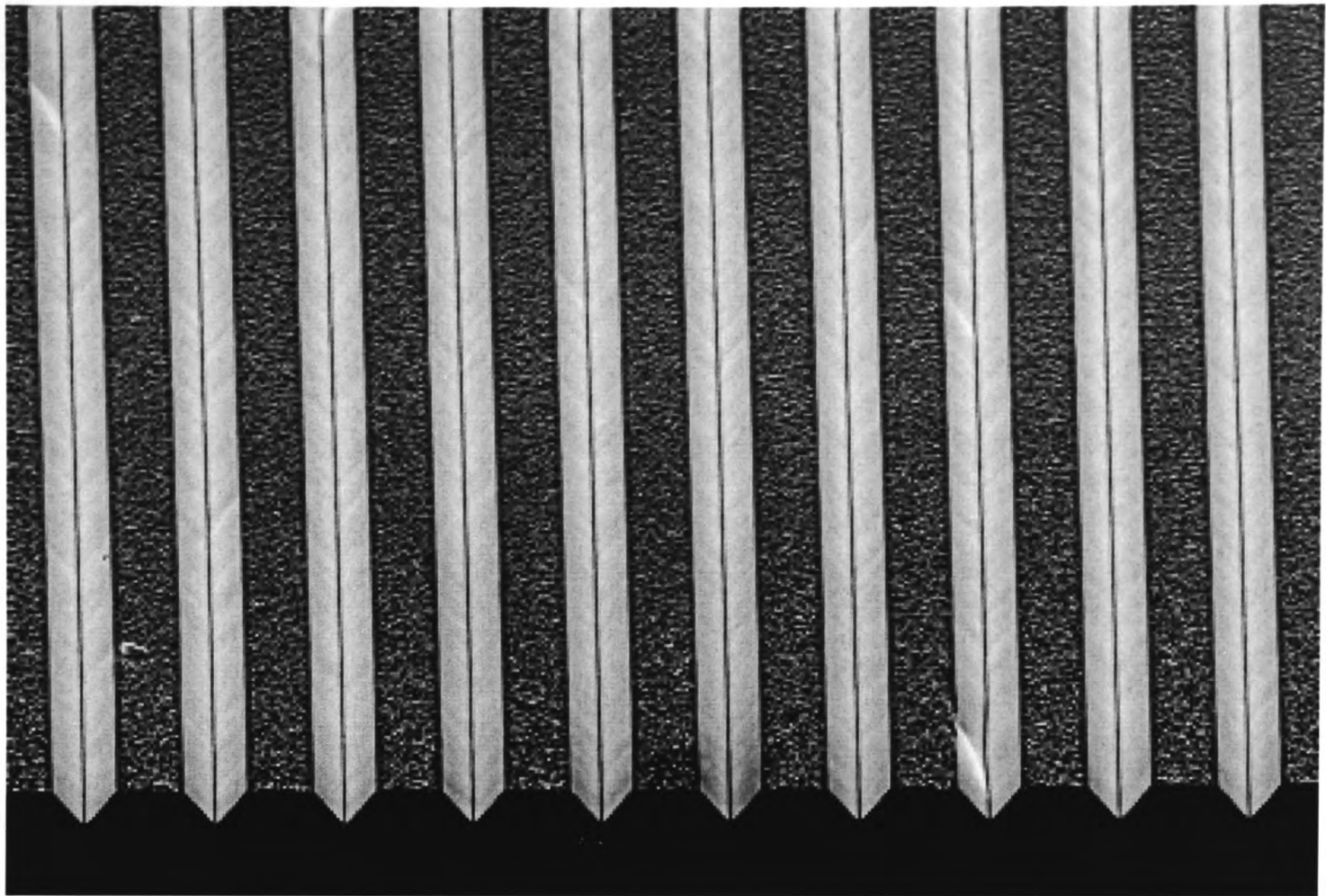


Figure 3.3: *Scanning electron microscopy picture of optical sample after MOCVD growth. Parallel running v-grooves with $1\ \mu\text{m}$ opening are separated by $1\ \mu\text{m}$ of polycrystalline material grown on the (100) surfaces.*

aligned under the mask, such that the v-groove stripes on the mask are parallel with the crystal orientation $[01\bar{1}]$; only then are the v-grooves etched correctly with two (111)A facets. After the exposure the illuminated photoresist is dissolved in developer solution, which makes the photolithographical process positive. The remaining photoresist forms a grid of stripes corresponding to the positive print of the grid pattern on the chrome mask. Since the chrome mask contains additional structures for the investigation of samples with electrical contact pads, these are developed simultaneously. Only before the metallization process, the structures for optical spectroscopy are separated from the ones for electrical measurements.

Before the SiO_2 is etched, the wafer is treated with reactive ion etching (RIE) to remove possible photoresist fog. To finally pattern the SiO_2 layer, the wafer is held in an HF solution

(AF91), where the oxide which is not covered by the photoresist is dissolved. The anisotropic RIE, which would achieve steep etch edges is not used for this process step, because the photoresist would harden and would therefore be difficult to remove. Besides the underetching of the SiO_2 during wet etching is negligible. After the SiO_2 has been patterned, the remaining photoresist is removed in a cleaning process with acetone and propanol.

Just before the epitaxial growth process, the v-grooves are etched in order to ensure the cleanest possible conditions for the wafer surface. The wafer is again treated in an acid to remove organic residuals and rinsed in deionised water. Then methanol is used to dissolve water from the wafer surface, since the etch solution bromine used in the following process, is not soluble in water. The etching of the v-grooves is finally carried out in a bromine:methanol solution, which etches selectively on (111)A crystal facets. This results in v-grooves with (111)A surfaces in $[01\bar{1}]$ direction. Depending on the width of the exposed GaAs stripes and the etch time, also u-grooves can be obtained. Etch times of 10 s and SiO_2 apertures less than $4\text{ }\mu\text{m}$ give v-grooves with only a narrow (100) strip, while larger widths produce significantly wider (100) planes on the bottom of the groove. In reference to the particular shape, the structures are called u-grooves. The layers on the (100) facets grown in u-grooves have two-dimensional properties and can be considered as quantum wells.

3.3 MOCVD GROWTH

The samples were grown with a low-pressure MOCVD system (Aixtron) at 650°C and a pressure of 20 hPa. Nitrogen was used as carrier gas instead of the more conventional hydrogen [Hardtdegen 1994a]. The installed sources for the growth of GaAs were trimethylgallium (TMGa) and arsine (AsH_3). For AlGaAs two different sets of precursors are available. The more common combination is trimethylgallium (TMGa) with trimethylaluminum (TMAI) and AsH_3 . Alternatively, AsH_3 can be employed with dimethylethylaminealane (DMEAA) and TEGa. The latter mix of sources has been found to

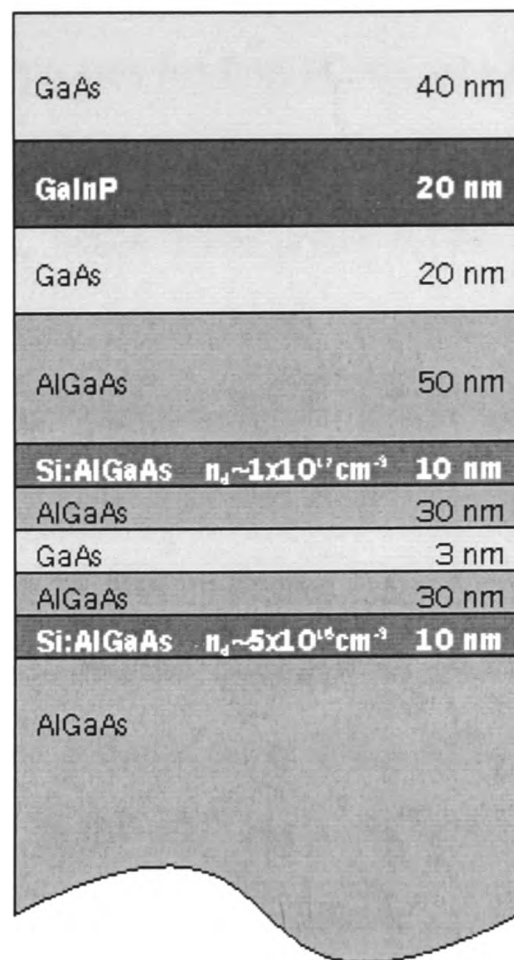


Figure 3.4: Typical MOCVD growth sequence for modulation-doped v-groove quantum wires. The doping layer, silicon doped AlGaAs, is separated by 30 nm from the GaAs channel layer. The lowest AlGaAs layer is a buffer layer and is grown on the GaAs substrate.

incorporate virtually no carbon into the grown AlGaAs, which leads to improved electrical properties [Hardtdegen 1994b]. It also does not develop a pronounced vertical quantum well, which excludes one source for optical transitions.

However, the foremost important property of the DMEAA/TEGa/AsH₃ combination is the initiation of polycrystalline growth on the SiO₂-mask. Presumably, DMEAA and TEGa are already decomposed in the gaseous phase, so that a desorption from the SiO₂ surface is inhibited. The polycrystalline growth insulates adjacent wires electrically from each other. This ensures in electrical experiments, where hundreds of single wires are connected in parallel, that conductivity perpendicular to the wires or parallel in the top quantum wells formed on the (100) surfaces is avoided. For this reason a typical growth recipe starts with the growth of a 300 nm Al_{0.3}Ga_{0.7}As buffer layer using the alane source (fig. 3.4). The

polycrystalline growth also suppresses loading effects which occur in the selective growth with standard precursors.

In the next sequence of layers, which corresponds to the growth of a modulation-doped quantum well, the TMAI/TMGa combination is used for the barrier material. This combination produces sharper curvatures on the bottom of the v-groove, which forms a more wire-like cross-section of the GaAs and therefore results in a better two-dimensional quantum confinement. 3 - 10 nm of silicon doped AlGaAs is then followed by a 20-30 nm AlGaAs spacer layer and the 3 - 10 nm thick GaAs quantum well. Then, mirroring the structure, a AlGaAs spacer layer, a doped layer and a AlGaAs layer are added. The doping concentration can vary between $2 \times 10^{16} \text{ cm}^{-3}$ and $2 \times 10^{17} \text{ cm}^{-3}$. The upper doping layer carries twice the amount of silicon atoms in the lower dopant layer in order to compensate the loss of carriers to surface states at the top of the structure.

In order to avoid the rapid oxidation of AlGaAs, when the samples are exposed to air, a GaAs layer covers the last barrier layer. Additionally, to improve the ohmic behaviour of contacts on top of the grown structure, needed for electrical experiments, a layer of highly doped GaAs and indium-ternaries can form the finish.

3.4 METALLIZATION

The samples which were used for electrical experiments had to undergo a metallization process to add contact pads at the ends of the quantum wires. These could then either be wired or bonded, depending on the needs and the feasibility. For structures which were primarily meant for electrical measurements specially developed chrome masks were used in a further photolithographical step. This was necessary as the contact pads were as small as $50 \times 60 \mu\text{m}$, designed to serve single QWRs. Optical samples with hundreds of parallel wires which had to be contacted were provided with $3 \times 3 \text{ mm}$ chrome contact pads sufficient to imprint the relatively large areas for the contact pads. In a negative photolithographical

process first the illuminated resist was hardened on a hot plate and then the entire sample flood exposed. Then only the photoresist in the contact pad area which was protected during the first exposure is dissolved in the developer bath.

Finally, a sequence of gold, nickel and gold/germanium layers are deposited in a metallization oven. In a subsequent ultrasonic acetone bath the photoresist is taken off together with metallization (lift-off), leaving only the metallization in the contact pad area.

To achieve a contact of the metallization with the buried GaAs quantum well layer, the metallized sample is thermally annealed in a rapid thermal annealer at temperatures above 1100 °C. This leads to a dendritical penetration of the metals into the upper layers down to the GaAs well layer.

Large pads used for optical samples can easily be glued to thin copper wires with silver dag, while the smaller pads on electrical samples have to be installed in a chip carrier and bonded.

3.5 STRUCTURAL ANALYSIS

A first investigation of the samples under a light microscope or even by looking at the interference pattern generated by the hundreds of closely parallel packed v-grooves by eye gives a first impression of the macroscopic surface quality. However, only electron microscopy can give an insight into the crystal quality of the grown structure. The Jülich group made use of state-of-the-art facilities within their institute and provided high quality transmission (TEM) and scanning electron microscopy (SEM) pictures of the samples investigated in Oxford. The TEM pictures were done by Christel Dieker and Doris Meertens, while most of the SEM pictures were taken by H. P. Bochem.

SEM offers a vivid overview of the surface morphology of the sample on a scale from a few QWRs to the details of monolayers. Figure 3.5 shows one v-groove at the corner of a cleaved end. The difference between the crystalline grown semiconductor in the v-groove can clearly

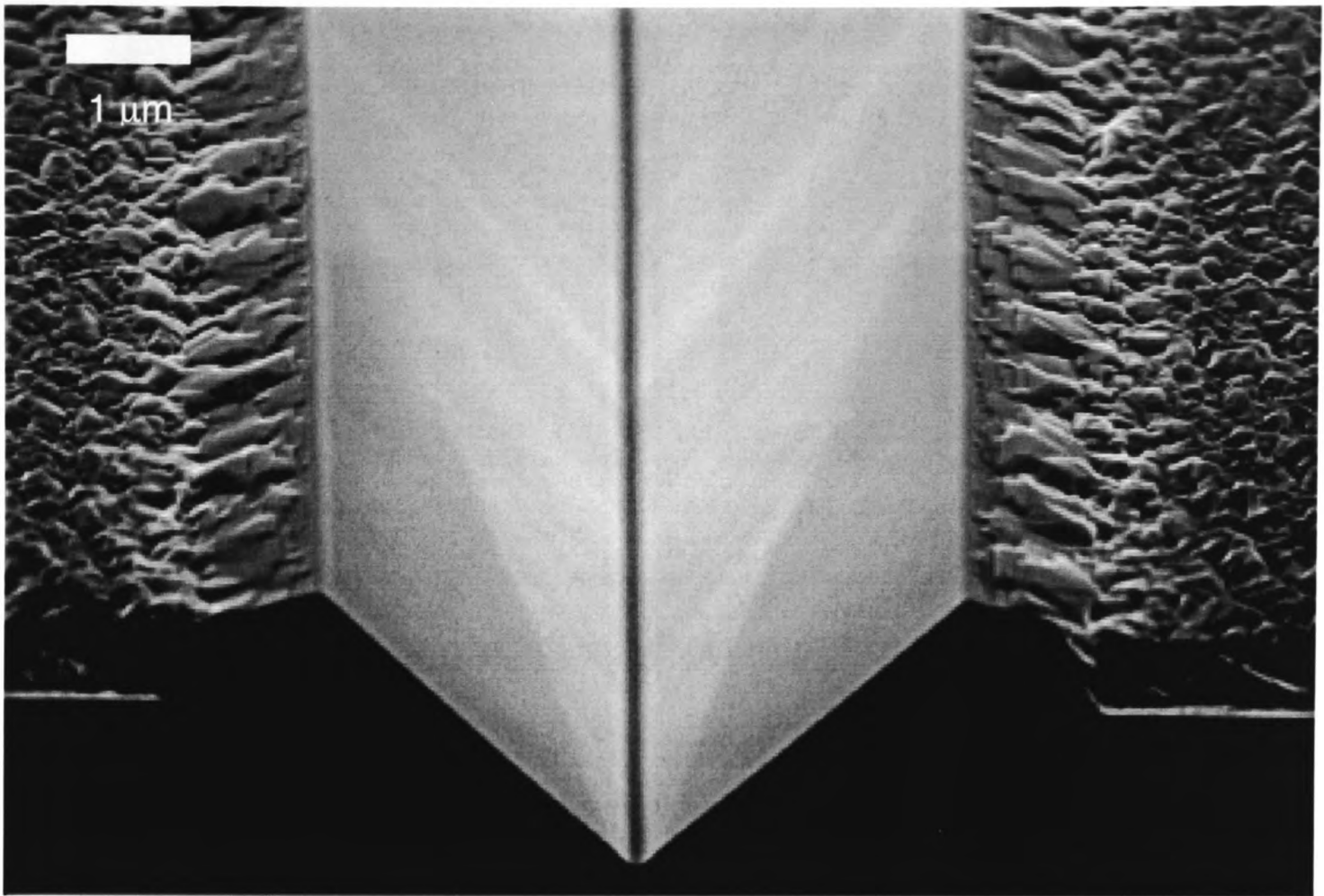


Figure 3.6: *Scanning electron microscopy picture of a v-groove after MOCVD growth. The v-groove (width: 2 μm) exhibits smooth layers on the $\langle 111 \rangle_A$ facets, while the flanking polycrystalline material appears rough as expected.*

be distinguished from the polycrystalline material to the left and the right. The amorphous growth is triggered by growth of AlGaAs with the DMEAA/TEGa/AsH₃ precursor set on SiO₂, which itself is amorphous and therefore prevents crystalline growth. The polycrystalline grown material exhibits poor conductivity and isolates neighbouring wires electrically from each other.

In the v-groove the surface is very smooth and uniform, indicating good crystal quality throughout the layers and therefore a successful fabrication process. In so-called u-grooves, where the (100) facet on the bottom of the groove is in the order of micrometers, even monolayer steps can be observed (fig. 3.6).

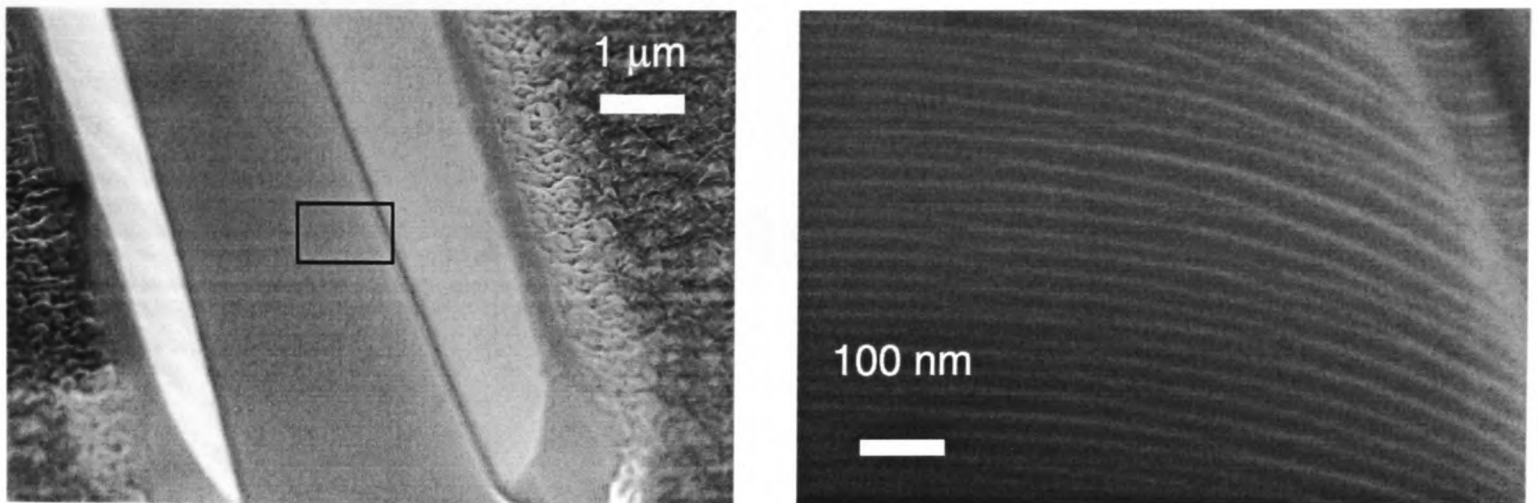


Figure 3.6: *Scanning electron microscopy picture of a v-groove after OMCVD growth. (a) Compared to v-groove structures, u-grooves have an additional (100) facet on the surface from the bottom of the groove. (b) On these facets, monolayer steps can be observed.*

The TEM picture in fig. 3.7 shows the wire region of a v-groove QWR. The dark v-shaped stripe is the thin layer of GaAs embedded in AlGaAs, which appears in lighter shades of grey. The long slopes of GaAs on the $\langle 111 \rangle_A$ facets represent two-dimensional structures and therefore have almost the same properties as a conventional QW. Here they are called side quantum wells (SQW). While the SQW towards the top of the v is limited by the polycrystalline grown material, it is pinched off towards the QWR at the bottom of the v-groove. The thickness ratio of SQW to constriction is crucial for the formation of the QWR and is 2:1 or larger in good quality samples. The pinch-off also gives rise to an energy barrier for the transport of carriers between the QWR and SQW due to the modified bandstructure. It is likely that the potential barrier is different in the valence band than in the conduction band. This would mean that the relaxation times of carriers from the SQW into the QWR depends on the type of the carrier. This possibility will be considered in chapter 8 when time-resolved photoluminescence measurements are discussed.

The QWR has a crescent shape and is about twice as thick in its centre than the SQW. The general mechanism of this self-organised growth is not entirely certain yet, but so far it is

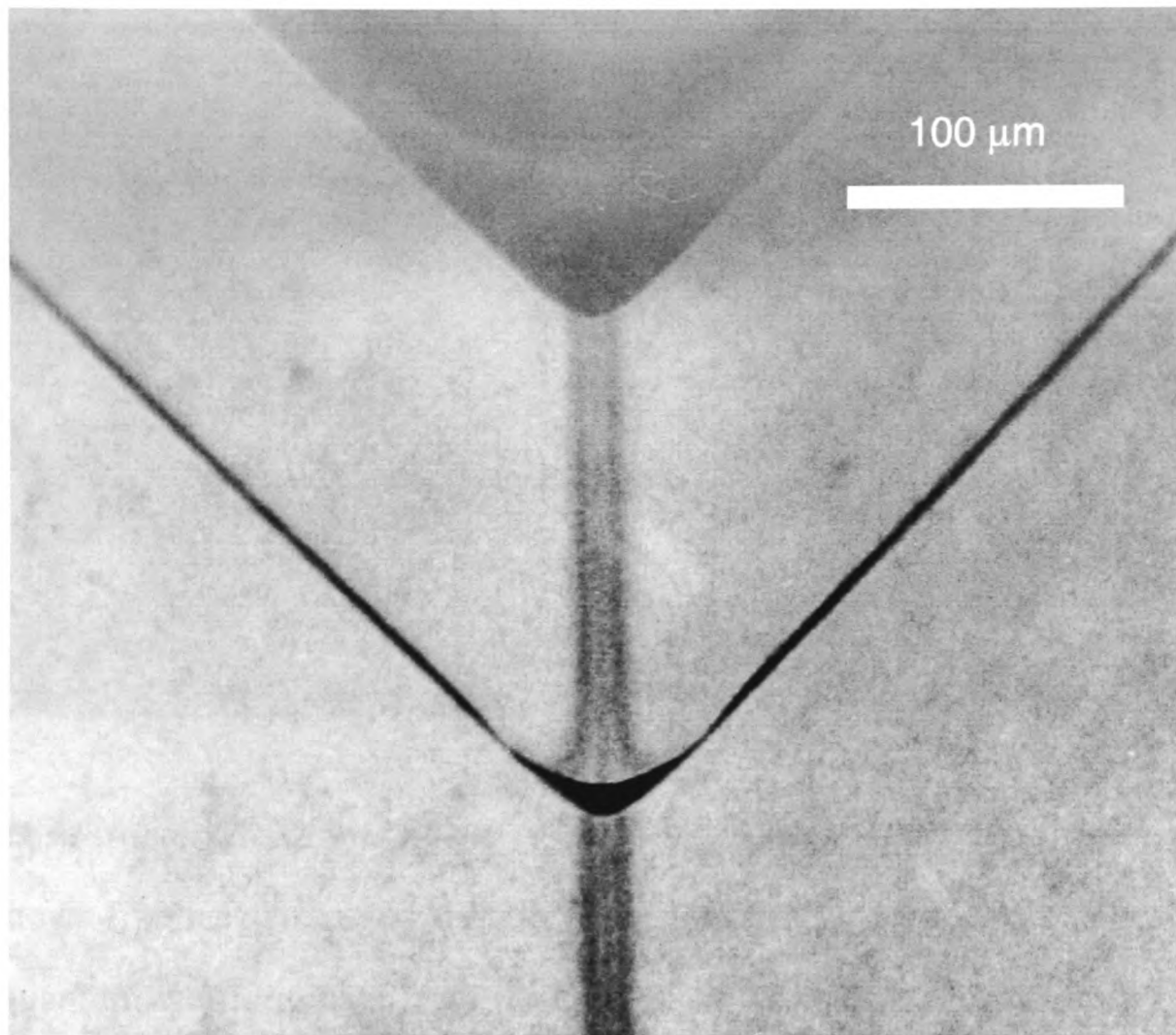


Figure 3.7: *Transmission electron microscopy picture of a v-groove quantum wire.* The shown sample exhibits the crescent shaped quantum wire with smooth interfaces and a strong pinch-off connecting it with the side quantum well. The vertical quantum well consists of three thinner vertical layers. The capping layers can be observed in the upper part of the picture.

understood that the shape occurs due to a preferential growth of GaAs on the narrow (100) facet on the bottom of the v-groove [Schwarz 1999]. The formation of the QWR shape is mainly determined by the curvature on the bottom of the v-groove before the GaAs deposition, the used source materials and the growth conditions such as temperature and gas flow rates [Schwarz 1997, Biasiol 1997a, 1998, Gustafsson 1995, Komori 1996].

Geometrical quantities which determine the shape of the QWR, like the ratio between the QWR and the constriction thickness or the size of the QWR cross-section, are obviously important parameters to obtain one-dimensional properties. These quantities were

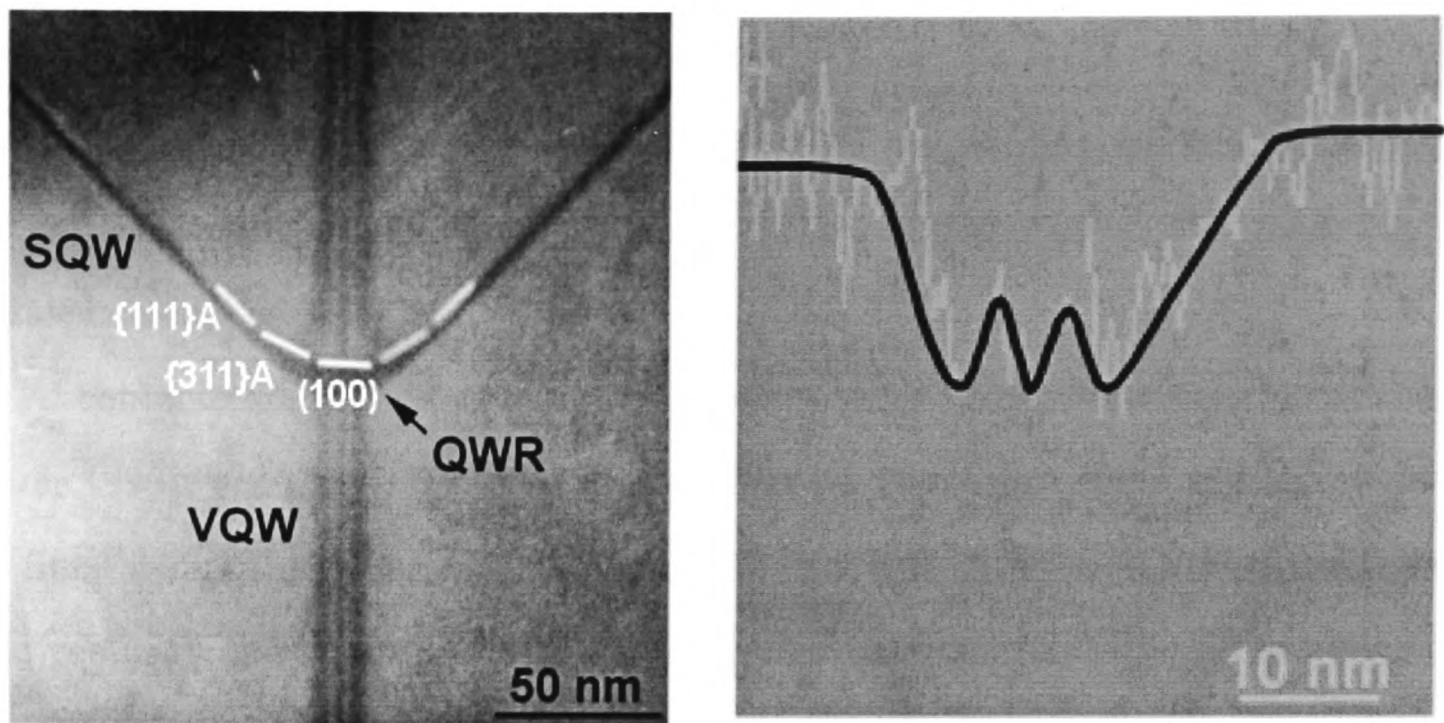


Figure 3.8: *Structural analysis of the vertical quantum well.* (a) The TEM picture shows five facets shaping the top of the QWR. The branches of the vertical quantum well originate from three of these facets ($\{311\}A$, (100)). (b) An energy dispersive x-ray analysis spectrum of the vertical quantum well, fitted a simulation, measures three minima of Al-concentration.

systematically varied by changing processing and growth parameters until optimal conditions were established [Kaluza 2000]. The influence of the geometric parameters on the electronic states has been investigated theoretically by O'Sullivan [2000] using the Poisson-Schrödinger solver described in chapter 2.5. High quality samples like the one in fig. 3.7 exhibit smooth and sharp interfaces, a well tapered QWR and virtually no dislocations or step-bunching. The TEM picture also shows a stripe of three dark-grey lines in the centre running vertically down from the bottom of the QWR. They are vertical layers of low Al-concentration AlGaAs and therefore represent weak QWs – they are therefore called vertical quantum wells (VQW). The entire set of VQW in the shown sample is about 12 nm thick and consists of one 2 nm thick layer in the centre and two flanking, 3 nm thick layers.

The origin of the VQW is related to the origins of the crescent shape of the QWR. A more detailed TEM picture of the VQW and its origin is shown in fig. 3.8. As it can be seen, five

facets shape the bottom of the v-groove: 2x {311}A, 2x {111}A and (100). If the TMAI/TMGa combination is used for the growth of the AlGaAs the Al-concentration is different for each local growth facet [Biasiol 1997b, Matinet 1997]. This results in three separate branches of the VQW.

The Al-concentration has been investigated with energy dispersive x-ray (EDX) analysis [Dieker 1999]. The EDX scan measured the intensity of the aluminium K-line, which was then fitted with a simulation taking into account the TEM specimen thickness, the electron probe geometry and the geometry of VQW. It was found that the Al-concentration profile was approximately 17 % in the dark areas and about 15 % in the lighter areas in between. So far, it has not been proved, whether the VQW acts as a one thick QW or as three individual QWs.

CHAPTER 4

EXPERIMENTAL ARRANGEMENTS

CONTENTS

4.1	INTRODUCTION	46
4.2	PHOTOLUMINESCENCE SET-UP	46
4.3	TIME-RESOLVED PHOTOLUMINESCENCE SET-UP .	49
4.4	ELECTRO-PHOTOLUMINESCENCE SET-UP	51
4.5	MAGNETO-PHOTOLUMINESCENCE SET-UP	53
4.6	PHOTOLUMINESCENCE EXCITATION SET-UP	53
4.7	MAGNETO-TRANSPORT MEASUREMENTS	
	SET-UP	56

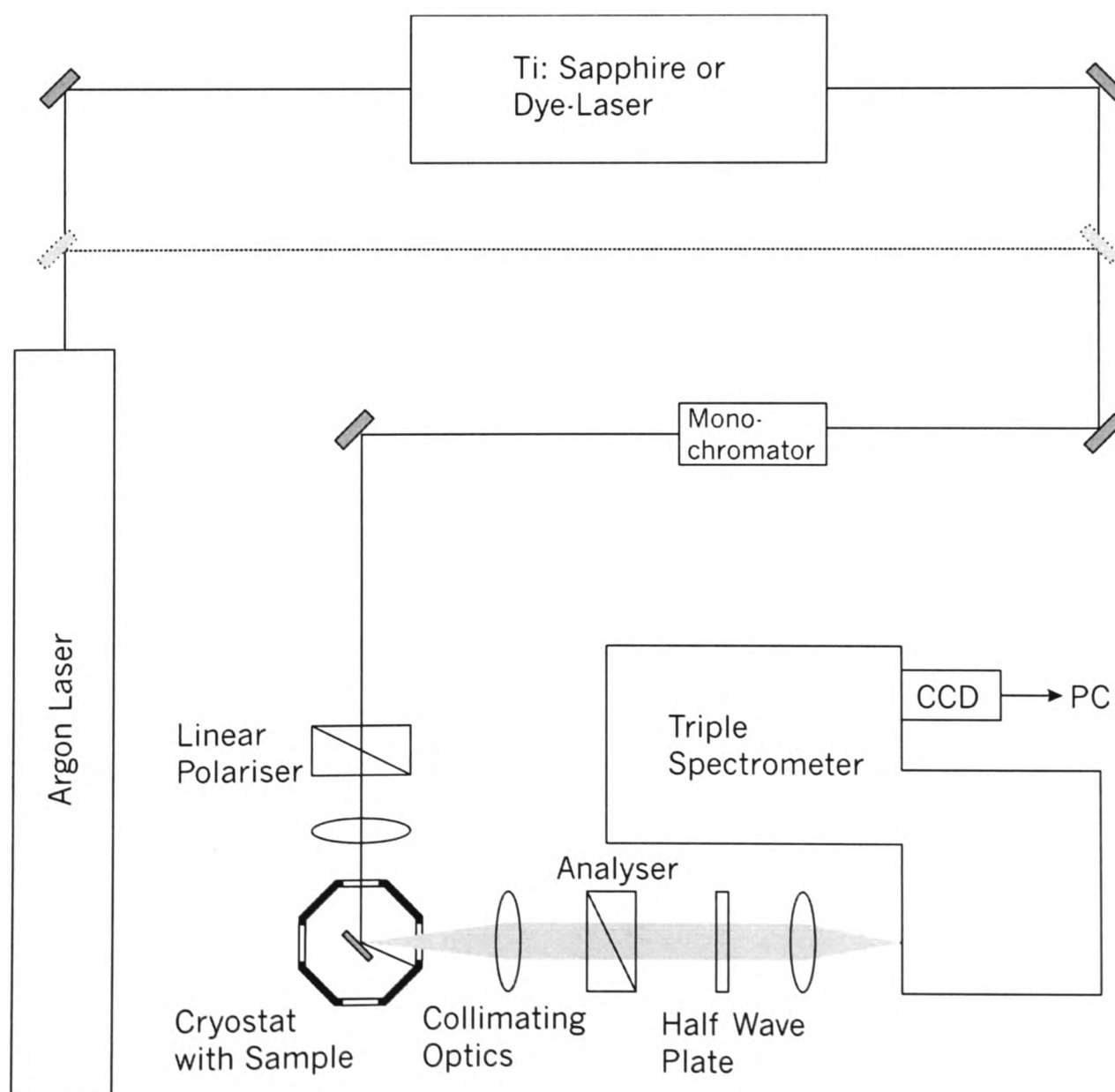
4.1 INTRODUCTION

The experimental results presented in chapters 6–9 were obtained with different methods of laser spectroscopy. The set-ups which were used are described in this chapter. The level of detail will be such, that it is sufficient to understand the conditions under which the measurements were performed and that it is possible to reconstruct the experiments. A general reading about the basic concepts and instrumentation in laser spectroscopy can be found in Demtröder [1996].

4.2 PHOTOLUMINESCENCE SET-UP

Time-integrated photoluminescence can be performed with different lasers (fig. 4.1),

Figure 4.1: *Photoluminescence set-up.*



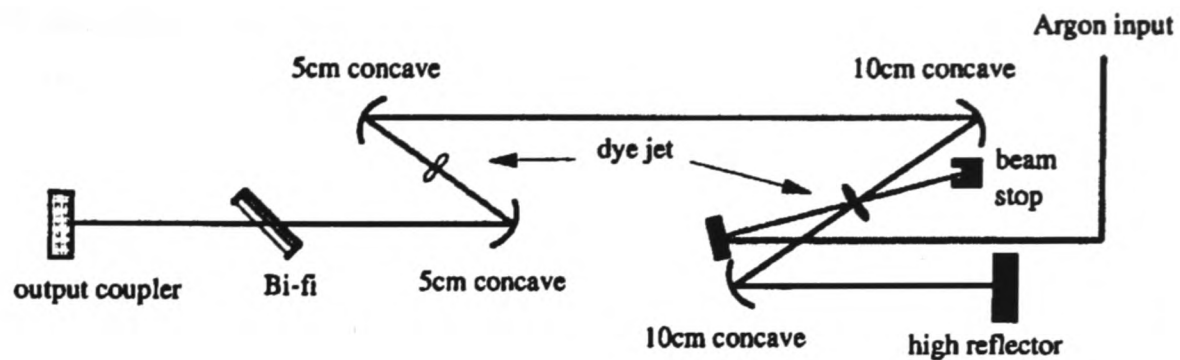


Figure 4.2: Schematic drawing of the hybrid mode-locked dye laser.

depending on the required wavelength, which are run in the continuous wave (cw) mode. For an excitation of the entire v-groove QWR structure, i.e. excitation energies above the barrier material $\text{Al}_{30}\text{Ga}_{70}\text{As}$, the 514 nm line of the Coherent Innova 400 argon is employed. A monochromator is used to select this spectral line from the over 15 transitions in Ar^+ , ranging from 350 - 514 nm. The output power can be modified with the size of the laser aperture or the power supply voltage. Typical output powers range from 5 W to 20 W which in most cases were reduced with neutral density filters down to several orders of magnitude less.

The argon also served as the pump laser for a Spectra Physics Tsunami Ti:Sapphire or a dye laser, when wavelengths outside the range of the argon were needed. The wavelength of the laser is tunable in the range of 690 – 1080 nm and output powers up to 12 W can be obtained. As a solid state laser, the Ti:Sapphire laser is less noisy, more stable and easier to operate than dye lasers.

The tunable dye laser, however, can be used with a range of different organic dyes, such as DCM, Pyridine, Rhodamine 6G with spectral windows ranging from ~560-740 nm. The dyes are dissolved in Glycol or Benzyl alcohol and sprayed through the cavity in a thin and defined jet (~ 50 μm). The pump laser hitting the jet at the Brewster angle with an uniform and thin spot excites the dye and in correct alignment of the laser optics causes the dye to lase (fig. 4.2).

The synchronously pumped hybrid mode locked dye laser used for this thesis was developed at the Clarendon Laboratory based on the design of Couillaud et al. [1985]. The output couplers have a transmission of 3 – 17 % and the dye concentration is usually chosen to

absorb 80 % of the pump laser power. Apart from the laser emitting dye jet, the laser can make use of an absorption jet within the second sub-cavity to suppress unwanted lasing wavelengths. The tuning of the wavelength is realised with a birefringent filter with double or triple plates (for details, refer to section 4.6).

The quasi-monochromatic beam from the laser can if necessary be reduced in intensity with neutral density filters and focused onto the samples with a 50 mm spherical or 60 mm cylindrical lens. Using the spherical lens the size of the laser spot can be as small as 50 μm and $2\text{ mm} \times 60\text{ }\mu\text{m}$ with the cylindrical lens. The cylindrical lens is preferred in cases, when very low excitation powers were needed; the elongated laser spot illuminates more area so that the level of the collected signal is relatively high.

Almost all photoluminescence experiments were performed in a helium flow cryostat (Oxford Instruments) under helium cooling at temperatures down to 4 K. Up to four samples were installed into the cryostat at once. To ensure good thermal conductivity they were glued with GE varnish onto a copper sample holder. The temperature is measured with a diode and adjusted with a custom made temperature controller.

The luminescence from the sample is collected and collimated with a 58 mm camera lens onto a second lens which focuses the light onto the spectrometer slit. To investigate the luminescence polarisation anisotropy in one-dimensional semiconductor structures a polariser and an analyser are introduced in the excitation beam and the collimated light path respectively. The polariser sets the linear polarised incident light to be perpendicular or parallel to the quantum wires, while the analyser allows to take polarised and depolarised spectra. A broadband half-wave plate in front of the spectrometer ensures that the polarisation incident on the gratings of the spectrometer is always vertical, regardless of the orientation of the analyser. This is due to the fact that the throughput of the spectrometer depends on the polarisation.

For the spectral analysis of the collected light a SPEX Triplemate spectrometer is used. It contains a two-stage filter (subtractive dispersion) with 0.22 m focal length and two 600 lines/mm gratings. They achieve a light rejection ratio of 10^{14} at 10 band-pass units away from the laser. A further dispersive stage with 0.6 m focal length contains three interchangeable gratings with 300, 1200 and 1800 lines/mm. The analysed light is then read out by a 512×512 pixel charge coupled device (CCD). Using the 1800 lines/mm grating, the

highest obtainable resolution is 0.02 nm. The signal from the CCD is then acquired by a personal computer, equipped with a data acquisition card and data analysis software.

4.3 TIME-RESOLVED PHOTOLUMINESCENCE SET-UP

Time-resolved PL measurements require the generation of short laser pulses, which can be realized by mode-locking. This technique produces short laser pulses by superpositioning allowed modes in a laser cavity such that the frequencies have a uniform phase and amplitude relationship [Yariv 1989]. The more modes are locked the shorter and higher the pulses become. An essential condition for the coupling of the modes is the energy exchange of the modes in the cavity. This can be induced by active or passive mode locking. In the passive method a modulator in the cavity transmits only the modes, which already have a fixed phase relationship. The active mode-locking initiates a large number of modes first and then creates an enhancement of the coincidentally coupled modes.

The excitation source used for time-resolved photoluminescence experiments in this thesis was a combination of an actively mode-locked argon laser and a synchronously pumped dye laser (fig. 4.3). The active mode-locking of the argon laser is done with an acousto-optic modulator within the laser cavity driven by an RF source. The frequency of the RF source is 38 MHz and equivalent to half a round trip of the light in the cavity. The RF field introduces a stress diffraction grating in the modulator prism with maxima at twice the frequency. This causes periodic losses in the cavity and locks the cavity modes to the driving frequency of $c/4L_{cav}$. The laser is then mode-locked at a repetition frequency of 76 MHz. The average power used was around 800 mW and the pulsed length 100 ps.

The same pulse frequency is produced in the dye laser by synchronously pumping with the argon laser. This is possible, when the cavity length of the dye laser is matched to the cavity length of the argon laser. Under this condition the generated dye laser pulse will be incident on the dye jet after one round trip at the same time as the next pump pulse. The gain in the jet will deplete very quickly due to stimulated emission, so that the generated pulse is much shorter than the pump pulse.

The synchronous pumping is combined with passive modelocking to produce a so called hybrid modelocking achieving even shorter laser pulses. The passive modelocking in the dye

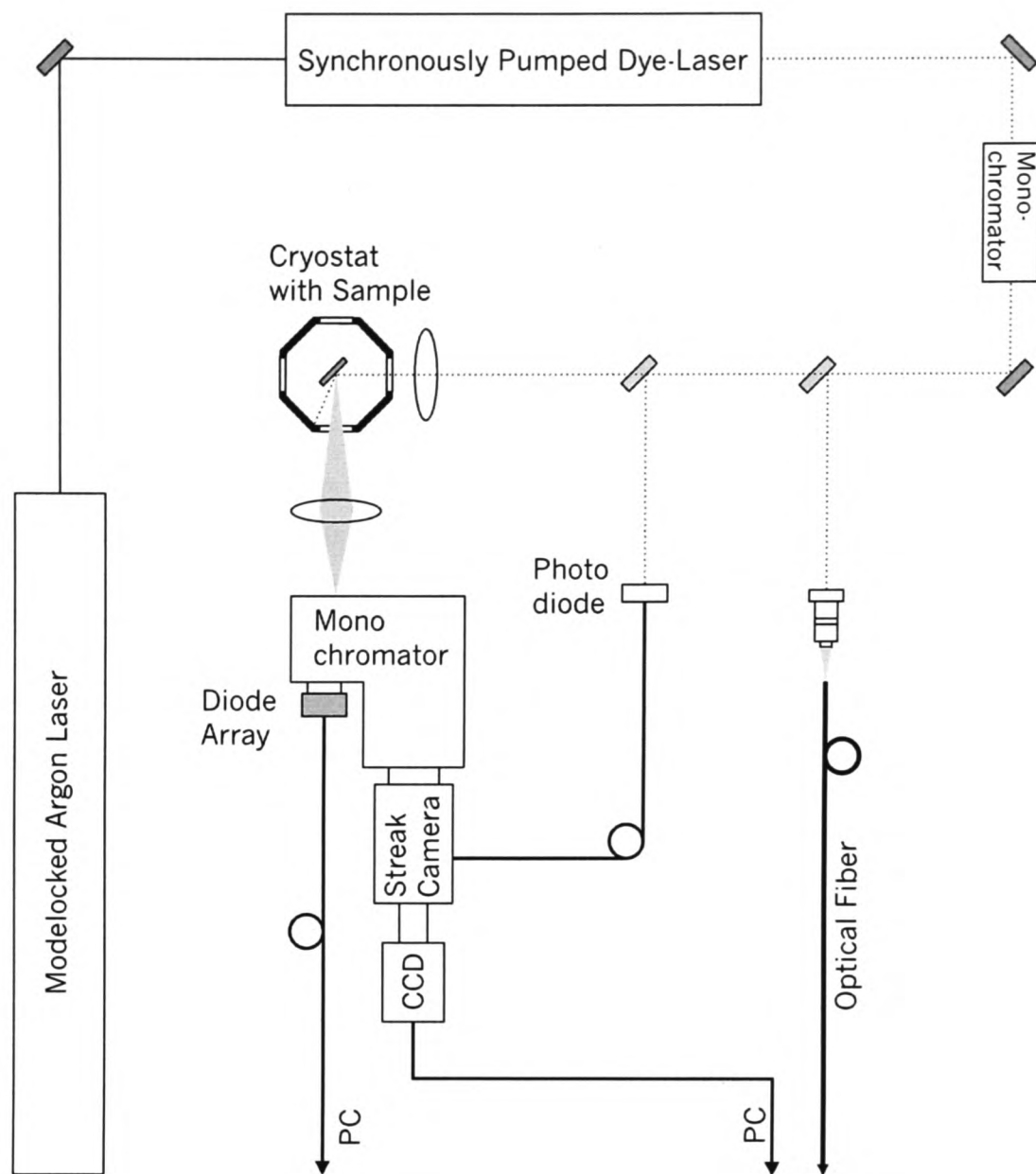


Figure 4.3: *Time-resolved photoluminescence set-up.*

laser is realised by a saturable absorber jet inserted in the laser cavity. The absorber, usually a weak organic dye solution, suppresses low intensity radiation and transmits preferably high intensity radiation, leading to modelocking. By hybrid modelocking temporal pulse lengths of 500 fs can be obtained. This time scale is small enough to probe picosecond processes in semiconductors, like the carrier relaxation processes in quantum wells and quantum wires. The Ti:Sapphire laser could not be used since the modelocking frequency of this laser was different to the resonance frequency of the detecting streak camera.

For the time-resolved PL measurements the samples were usually mounted in a microscope cryostat (Oxford Instruments). Spherical lenses are used to focus the excitation laser onto the sample, collect and collimate the luminescence and focus it on the monochromator slit. Two low intensity beams are split off from the main beam before the sample. One is detected by

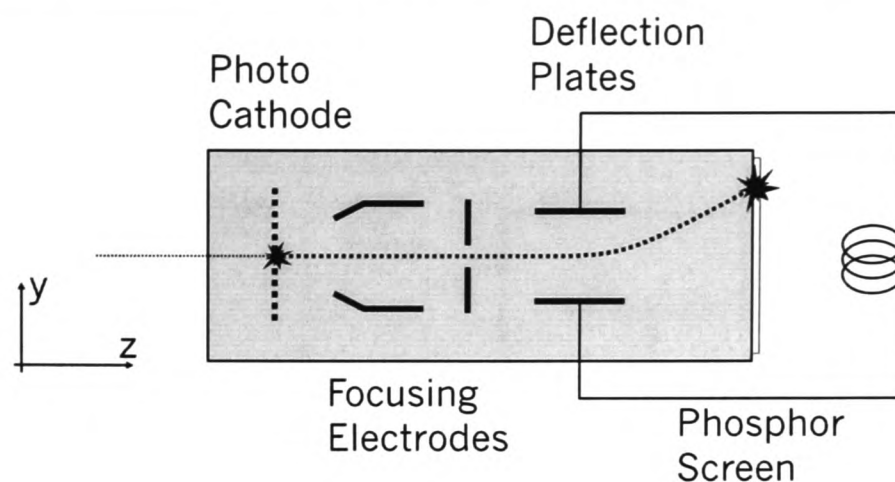


Figure 4.4: *Schematic drawing of streak camera.* The trajectory of an electron through the cathode ray tube is shown exemplarily.

an ultrafast photodiode, which provides the trigger signal for the streak camera and the other one serves as a marker pulse for the time calibration of the spectra.

The luminescence is analysed in a subtractive dispersion double spectrometer so that only a single wavelength enters the streak camera where it is temporally resolved. Alternatively, the luminescence signal can be mirrored onto a diode array to monitor the time-integrated photoluminescence spectrum. In the streak camera (Hadland Photonics Imacon 500), the photoluminescence pulse is focused onto a photo-cathode, where it produces a number of photoelectrons proportional to the time profile of the optical pulse (fig. 4.4). Electrodes focus the electrons between a pair of deflection plates. Applying a sinusoidally-varying voltage ramp to the deflection plates the pulse is transferred from a z -distribution into a y -distribution. The frequency of the sinus is given by the trigger signal from the photodiode. The profile in the y -direction is then projected onto a luminescent screen and read out by a CCD. The distribution on the screen therefore reflects the time profile of the incident light pulse. The time resolution of the streak camera is 20-30 ps, mainly due to the jitter in the sinusoidal trigger. The signal is acquired by a computer with an AT1 card and processed with the AT1 software.

4.4 ELECTRO-PHOTOLUMINESCENCE SET-UP

In electro-photoluminescence the investigated samples are contacted electrically and a voltage is applied along the quantum wires. The PL spectrum is then taken and the effect of

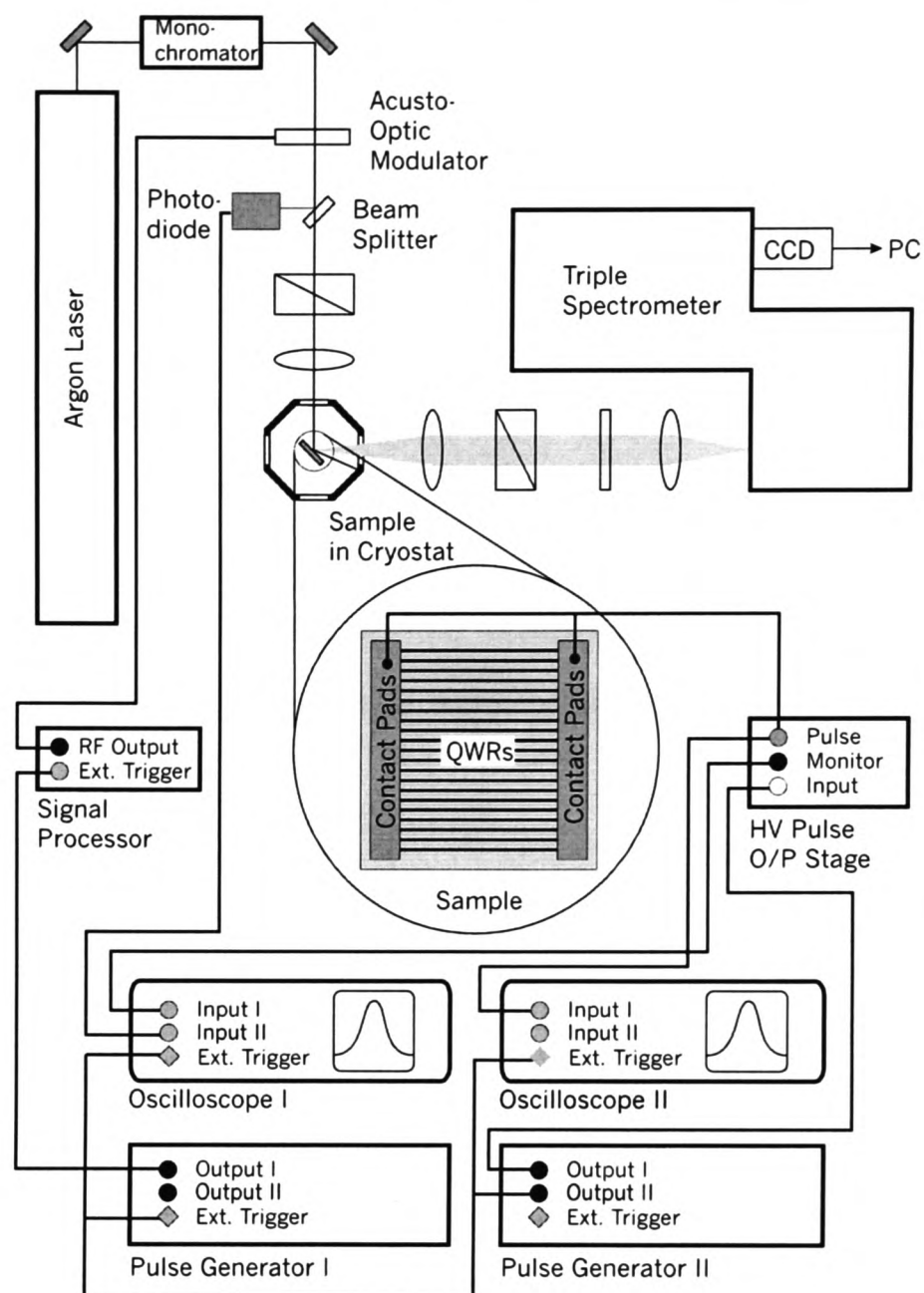


Figure 4.5: *Set-up for electro-photoluminescence experiments.* A pulsed electrical current - synchronised with the laser pulses - is applied along the quantum wires.

the electrical field on the spectrum is analysed. The samples were first equipped with contact pads on both ends of the QWRs as explained in chapter 3.4 and wired to the socket pins at the top of the sample holder.

When performing the electro-photoluminescence measurements, an unwanted increase of the lattice temperature can occur due to scattering of accelerated electrons with the lattice. To avoid lattice heating the applied current is pulsed. The pulse lengths and the intervals have to be such that no or only a small heating effect can be observed. Pulse lengths of $2 \mu\text{s}$ and a duty cycle of 0.95 produced by a pulse generator (Fig. 4.5 Pulse Generator II, Pulsetek Pulsegenerator 233) proved to work well for the investigated samples.

Depending on the magnitude of the voltage and the precision required for the voltage control, either a pulse generator (Pulse Generator II) or for voltages above 7 V a custom made high voltage pulse output stage (HV Pulse O/P stage) was used. In the case when the high voltage supply was employed, it was triggered by the Pulse Generator II with a 5 V TTL pulse.

To take the optical spectra the laser has to be pulsed synchronously with the electrical pulses. For this purpose, the output signal from a second pulse generator (Pulse Generator I), triggered itself by Pulse Generator II, is connected to a signal processing unit, which translates the pulses into an RF signal for the acousto-optic modulator. The coincidence of the optical pulse with the electrical signal is monitored and adjusted on an oscilloscope.

4.5 MAGNETO-PHOTOLUMINESCENCE SET-UP

The set-up for magneto-photoluminescence is a simple modification of the photoluminescence set-up using an argon laser as excitation source (fig. 4.6). Instead of the optical cryostat, the sample is installed into a He-cooled Superconducting Magnet (Oxford Instruments) which produces magnetic fields of up to 15.5 T at 1.4 K. One optical fibre is used as a light coupler to feed the laser into the cryostat, directly shining it onto the sample and also to collect the emitted light. A fibre-optic switch couples the photoluminescence into a second fibre which leads to the triple spectrometer. The data acquisition of the spectrum is the same as in the photoluminescence set-up.

4.6 PHOTOLUMINESCENCE EXCITATION SPECTROSCOPY

The set-up for photoluminescence excitation experiments distinguishes itself from a PL set-up essentially only by a continuously tuned excitation source; during a measurement the luminescence is detected at a fixed wavelength (in general at the high energy shoulder of a PL peak), while the laser is tuned from just above this given energy to higher energies. The resulting spectrum corresponds basically to an absorption spectrum.

The system presented here (fig. 4.7) uses an argon-pumped dye laser with LD700 which is tuned by a stepper motor rotating the birefringent filter in the cavity and covering a

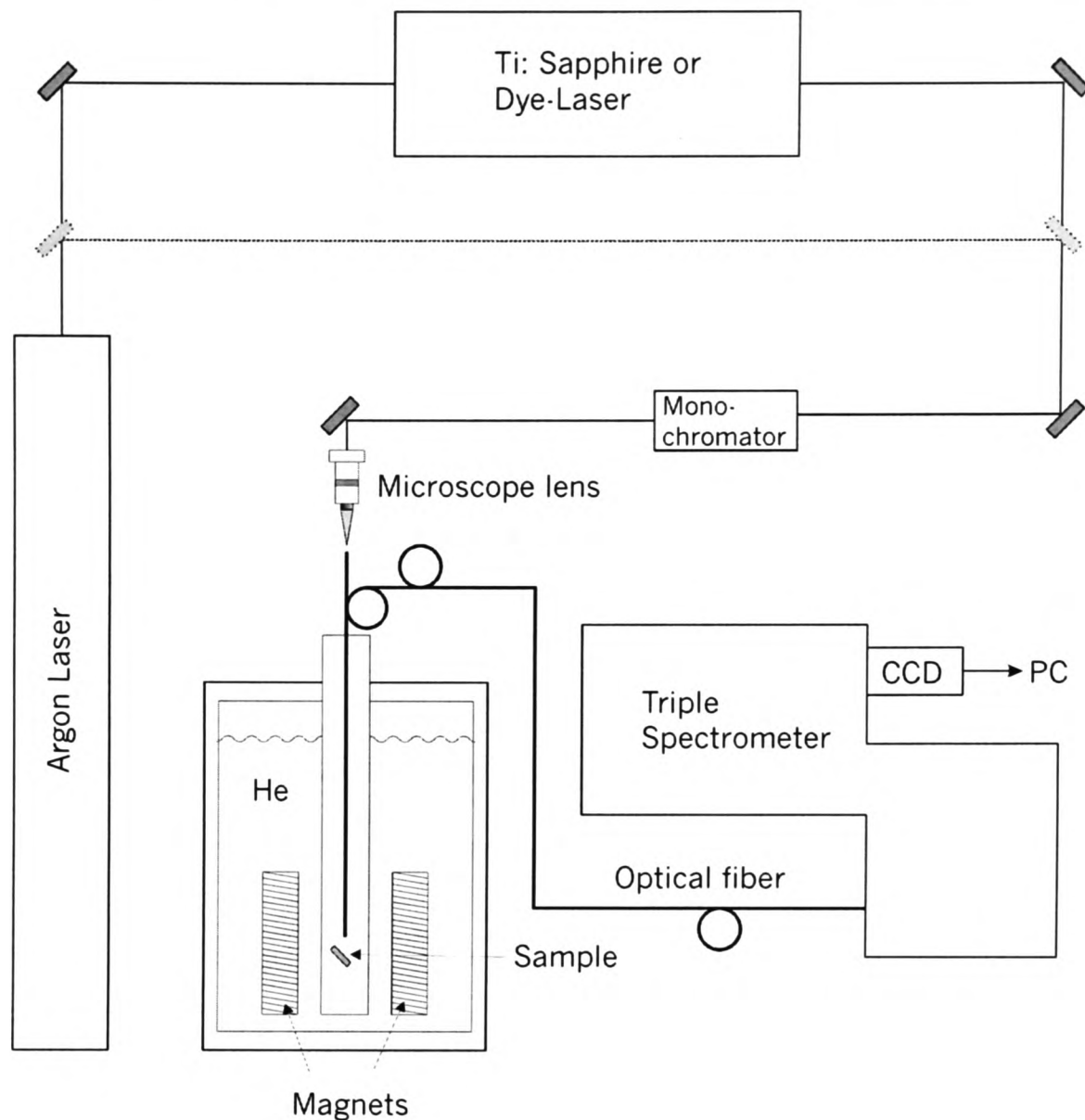


Figure 4.6: *Set-up for magneto-photoluminescence experiments.* The He-cooled superconducting magnet used in this set-up generates fields up to 14 T. The light was transmitted by optical fiber into and out of the cryostat.

wavelength range of $\sim 680 - 790$ nm. Due to the wavelength dependent loss, the turning of the filter results in a continuous wavelength selection within certain ranges. The plates are made of crystalline quartz and their optical axis are in the plane of the filter disc. The phase shift of the ordinary and extraordinary rays induced by the filter is described by

$$\delta = \frac{2\pi}{\lambda} n_{o,e} d, \quad (4.1)$$

where d is the thickness of the birefringent material, λ the wavelength of light in vacuum and $n_{o,e}$ are the refractive indices for the ordinary and extraordinary rays respectively. Due to the phase shift of the two rays the initially linear polarised light becomes elliptically polarised

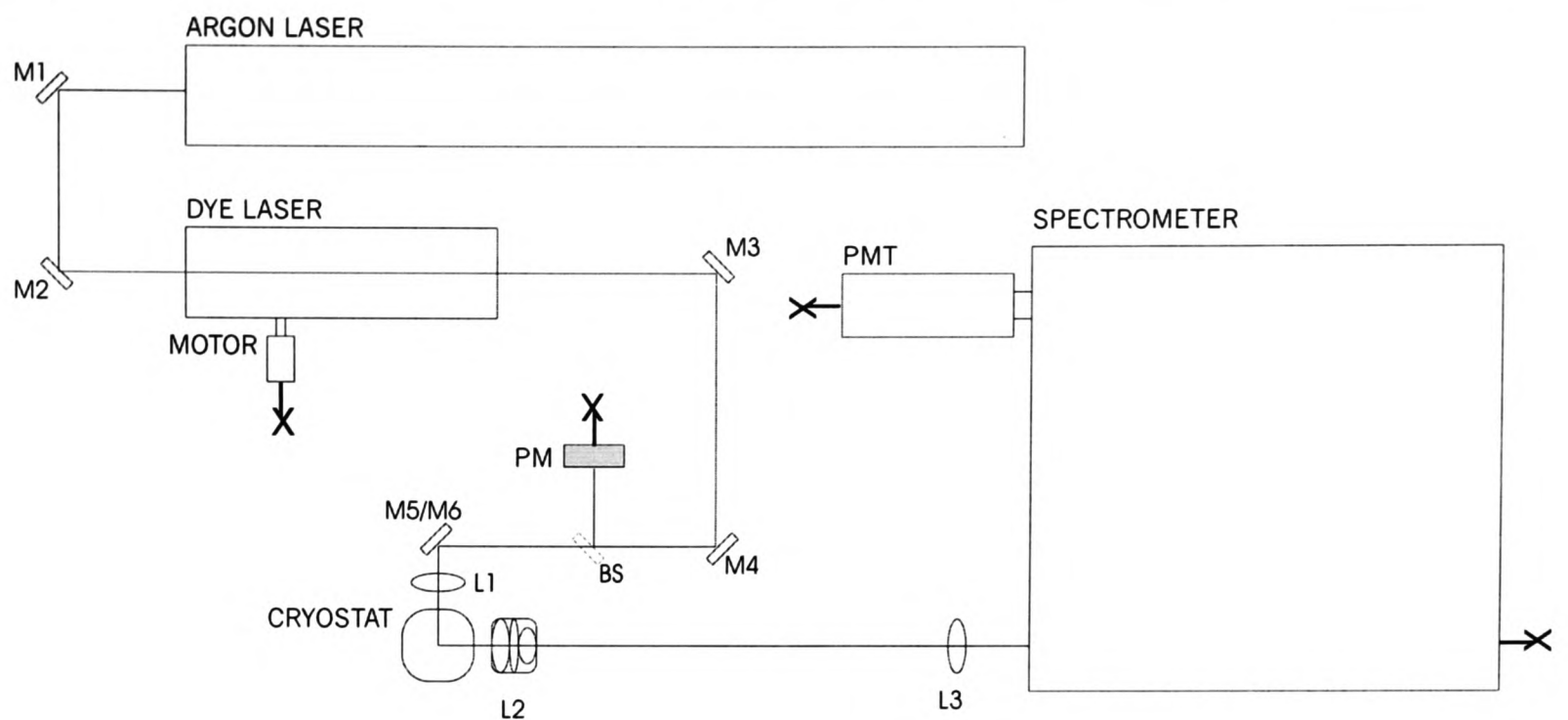


Figure 4.7: *Photoluminescence excitation set-up.* M1-6: mirrors. L1-3: lenses. PM: photometer. BS: beam splitter. PMT: photomultiplertube. ×: leads to the control box.

for most of the wavelengths. These wavelengths experience losses at polarisation sensitive cavity elements such as the filter itself or the Brewster-angled dye laser. Only in the case where λ is such that the phase shift is a multiple of π does the light remain linearly resulting in lasing.

To take a spectrum the tuning of the laser was synchronised with the detection system, consisting of a spectrometer and a photomultiplier tube (PMT), through a control box and a PC data acquisition (DAQ) card (Amplicon DT301). The control box was developed in order to drive the motor for the wavelength tuning and the acquisition of the spectrum, but also to monitor the laser intensity through a photometer which measured the intensity of a weak beam, split off from the main laser beam. This information was used to normalise the spectrum with the excitation intensity. PL spectra could be taken with the same system, as the control box was programmed to tune the spectrometer instead of the laser. The programming software Labview was used to programme the control box and acquire the data. The samples were cooled in a helium-flow cryostat.

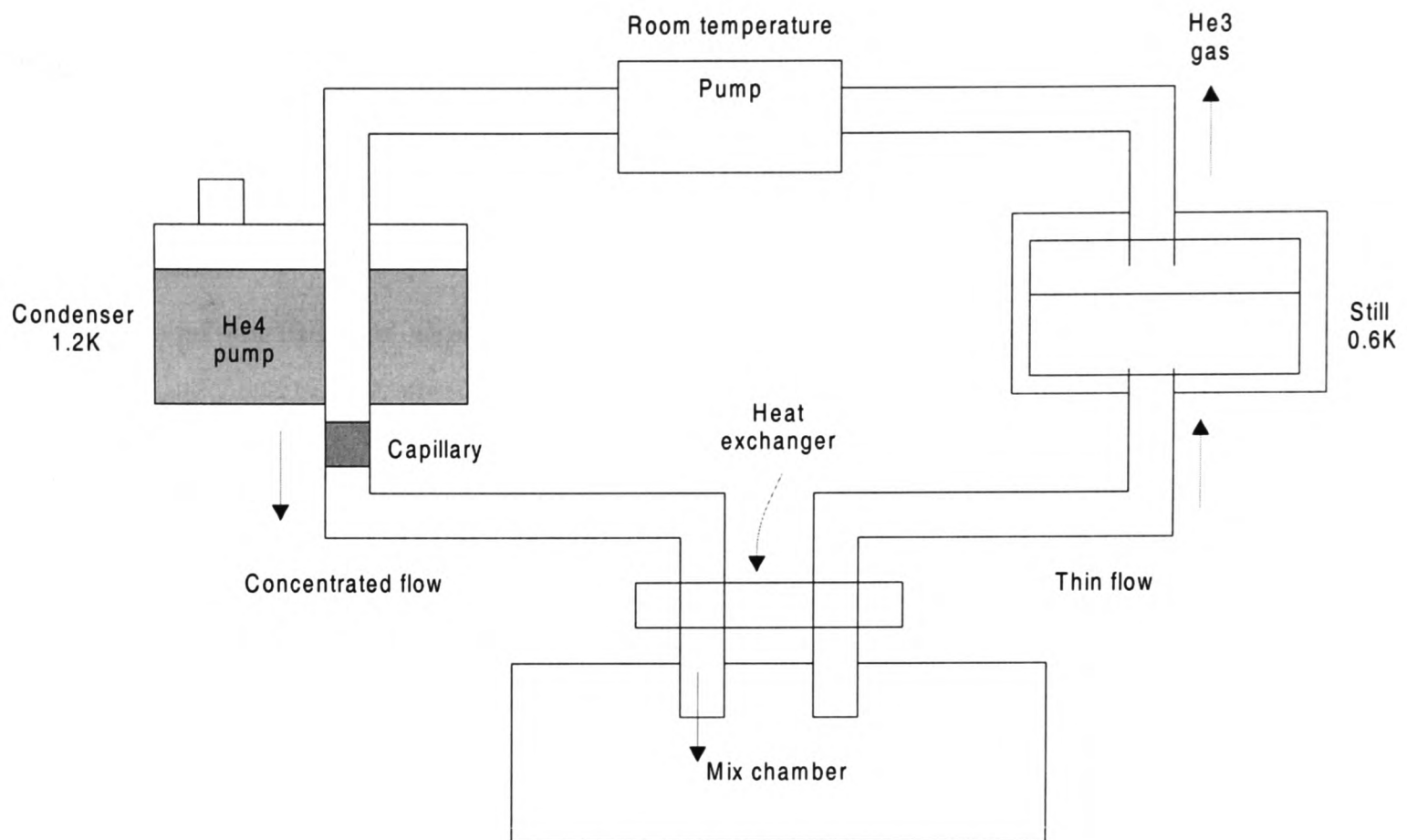


Figure 4.8: *Set-up of a He^3/He^4 cryostat.* For magneto-transport measurements samples were cooled in an Oxford Instruments TLM400 He^3/He^4 cryostat.

4.7 MAGNETO-TRANSPORT MEASUREMENTS SET-UP

To investigate the quantum mechanical effects of low-dimensional transport, as e.g. the deviation of the Shubnikov-de-Haas oscillations from the inverse magnetic field, the samples have to be kept at very low temperature. While in flow cryostats temperatures of 1.4 K can be achieved, in He^3 -cryostats 300 mK are possible. However to detect highly temperature sensitive behaviour as quantum interference effects, even lower temperatures have to be used. This can be accomplished by using a $\text{He}^{3/4}$ -mix cryostat. For the experiments in this thesis a Oxford Instruments TLM400 was used, where temperature 30 mK can be reached.

The set-up of the cryostat is shown in figure 4.8. Due to the higher steam pressure pumping at the still leads to the preferential evaporation of He^3 from the mix. The withdrawn evaporation heat cools down to a temperature, where two phases separate. The He^3 rich layer

is called concentrated and He^4 rich layer thin phase. Further pumping at the still leads to evaporation of He^3 from the thin phase, so that He^3 continuously moves into the thin phase. This two phase transition allows efficient cooling down to 30 mK. The evaporated He^3 is first filtered in cooling traps, where contaminations are frozen out, and is then reliquified in the condenser.

The cryostat includes a superconducting magnet, similarly to the one used for magneto-optical measurements, which produces magnetic fields up to 16 T. For the signal acquisition regular lock-in techniques with sample currents of 10 nA was used.

The samples were glued and bonded onto a chip carrier and then tucked onto a sample holder. For angle-dependent measurements a specific sample holder was developed which aligns the sample in angles of 0° , 15° , 30° , 45° and 90° relative to the applied magnetic field.

CHAPTER 5

OPTICAL PROPERTIES OF UNDOPED V-GROOVE QUANTUM WIRES

CONTENTS

5.1	INTRODUCTION	59
5.2	OPTICAL PROPERTIES OF UNDOPED SAMPLES	60
5.3	RESULTS FROM THE SCHRÖDINGER SOLVER	67
5.4	OPTICAL TRANSITIONS IN APPLIED MAGNETIC FIELDS	69
5.5	HIGH EXCITATION POWER EXPERIMENTS	77
5.6	PHOTOLUMINESCENCE EXCITATION SPECTRA	81
5.7	CONCLUSIONS AND OUTLOOK.....	84

5.1 INTRODUCTION

The optical properties of undoped v-groove QWRs have been the subject of numerous publications since the successful realization of the first samples in 1987 [Kapon 1987]. Low temperature photoluminescence (PL), PL excitation (PLE) and cathodoluminescence (CL) spectroscopy have been used to establish the formation of 1D subbands [Kapon 1992, Walther 1992, Gustafsson 1995, Wang 1995]. A large part of the research has also dealt with carrier dynamics especially in structures with superlattice barriers, investigating e.g. electron capture into the QWR [Ryan 1996], hot carrier relaxation [Maciel 1995], carrier life times [Christen 1992, Oberli 1999] and the role of the VQW in carrier capture [Kiener 1996b]. Theoretical models have been developed in order to calculate the mixing of the valence bands [Vouilloz 1998], to determine electron states in v-groove QWRs with superlattices [Kiener 1996a] and to examine the role of Coulomb correlation in absorption spectra [Rossi 1996b].

This chapter presents the results of optical experiments on undoped v-groove QWRs which were obtained by time-integrated PL, CL, PLE and magneto-PL (MPL) measurements and are analysed in conjunction with calculations of a Schrödinger solver. The results confirm the successful fabrication of 1D quantum structures and allow the identification of optical transitions. The undoped samples were fabricated in sets with modulation-doped v-groove QWRs which were grown with nominally identical epitaxial parameters, apart from the additional dopant layers. The characterisation of these doped samples follows in chapter 6. There, the results of this chapter serve as reference in the analysis of the doped structures; the undoped samples can demonstrate the degree of success of the general fabrication process and give an insight into the optical properties of the structure without the dopant layers.

Furthermore, some novel findings will be reported here: At increased photoexcited carrier densities a suppression of excitonic recombination due to many-body effects has been

observed, and as seen from PLE experiments an inefficient intersubband relaxation seems to be responsible for the appearance of the second QWR subband transition in PL spectra.

5.2 OPTICAL PROPERTIES OF UNDOPED SAMPLES

The PL experiments presented in the following were performed with an argon laser at 2.4 eV, well above the band-gap of the confining barrier material. The carriers excited in the barrier relax into the SQW and QWR and therefore contribute to a measurable PL signal. Unless stated otherwise, the spectra were taken with 0.1 mW laser power while the samples were kept at 7 K in a He-flow cryostat.

(a) Sample A1

The nominal thickness of the GaAs channel layer for sample A1¹ is 2.8 nm whereas in transmission electron micrographs (TEM) the thickness of the QWR has been measured to be 7.6 nm. The PL spectrum of sample A1 is shown in figure 5.1. The double peak at around 1.7 eV (dotted line) indicates the broad luminescence from the quantum well in the so called off-wire region. The off-wire region describes a 1 mm thick frame on the edge of each sample around the wire area and represents a straightforward quantum well with planar (100) interfaces. It can be considered an indicator for the quality of the fabrication and, moreover, serves as reference for the identification of the SQW. The difference in thickness between the quantum well in the off-wire region and the relatively thinner SQWs on the (111)A facets is due to different diffusion lengths of GaAs on the different facets during the epitaxial growth; the difference is only around 10 % which corresponds to a few meV in confinement energy for ground state excitons. The overlap of the corresponding PL is therefore expected and determines the peak at 1.709 eV (straight line, “on-wire region”) as PL from the SQW.

¹ Sample A1 corresponds to the doped sample A2 in chapter 6.

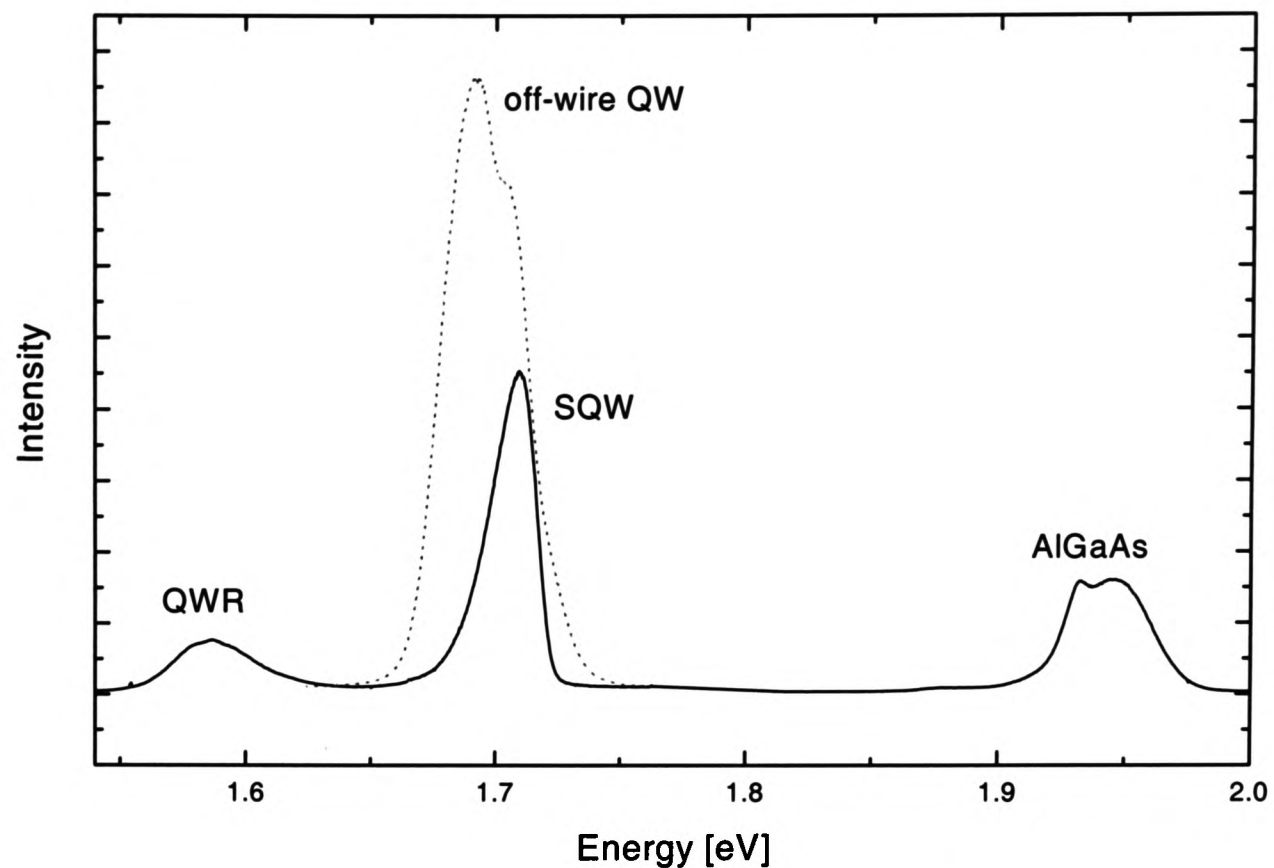


Figure 5.1: *Photoluminescence spectrum of undoped sample A1.* The spectrum exhibits luminescence peaks from the quantum wire (QWR), the side quantum well (SQW) and the barrier material $\text{Al}_{30}\text{Ga}_{70}\text{As}$. The off-wire quantum well luminescence peak exhibits a broad linewidth due to poor structural quality (dotted line).

This is also supported by a simplified calculation of the confinement energy for the given quantum well thickness with the Kronig-Penny model. The Kronig-Penny model strictly describes the confinement energies in a superlattice with (100) interfaces, not including excitonic effects [Cho 1987]. However, it can be used as an approximation for single-layer quantum wells by making the spacing between the well layers much larger than the well thickness. For the quantum well thickness of 2.8 nm an electron confinement energy of 142 meV is obtained². With a heavy hole confinement energy of 35 meV this results in a

² Used parameter: Well thickness: 2.8 nm, barrier thickness: 65 nm, Al-concentration: 30 %, temperature: 10 K, $E_G = 1.5194$ eV

recombination energy of 1.696 eV, which is in relatively good agreement with the experimental value.

The peak at 1.586 eV, which does not appear in the off-wire spectrum, originates from the QWR. At 7.6 nm it is almost three times as thick as the SQW and therefore has a considerably lower transition energy. In conjunction with the doped sample A2 further evidence for the assignment of the QWR transition will be given in chapter 6.2. The broad QWR linewidth of 30 meV is probably due to imperfect interfaces between the GaAs and the barrier material; rough v-grooves surfaces from the chemical etching during the fabrication can lead to thickness fluctuations along the wires, which induces inhomogeneous broadening of the PL line. Finally, at higher energies (1.93 - 1.97 eV) luminescence from the barrier material $\text{Al}_{30}\text{Ga}_{70}\text{As}$ can be observed.

The PL spectrum of Sample A1 is straightforward and demonstrates the successful fabrication of a v-groove QWR. However, the broad linewidths indicate that the quality of the grown structure is poor.

(b) Sample B1

The nominal thickness of the quantum well layer in sample B1³ is 3 nm. TEM pictures show that the thickness of the SQW is slightly thinner and measures 2.5 nm. The Kronig-Penny model yields a recombination energy of 1.734 eV for such a quantum well and identifies the peak right of the centre in the PL spectrum (fig. 5.2) as SQW luminescence. The emission from the SQW appears in CL pictures in a distinct v-shape (fig. 5.3 d and d').

The two sharp peaks in the PL spectrum at 1.591 eV and 1.636 eV are interpreted as excitonic transitions from the first and second wire subbands ($n = 1, 2$) of the 6.5 nm thick QWR. They can clearly be identified in cross section and overview CL pictures as shown in figures 5.3 e and e'. In fact, results obtained from the Schrödinger solver as well as PL

³ Sample B1 corresponds to doped samples B2 and B3 in chapter 6.

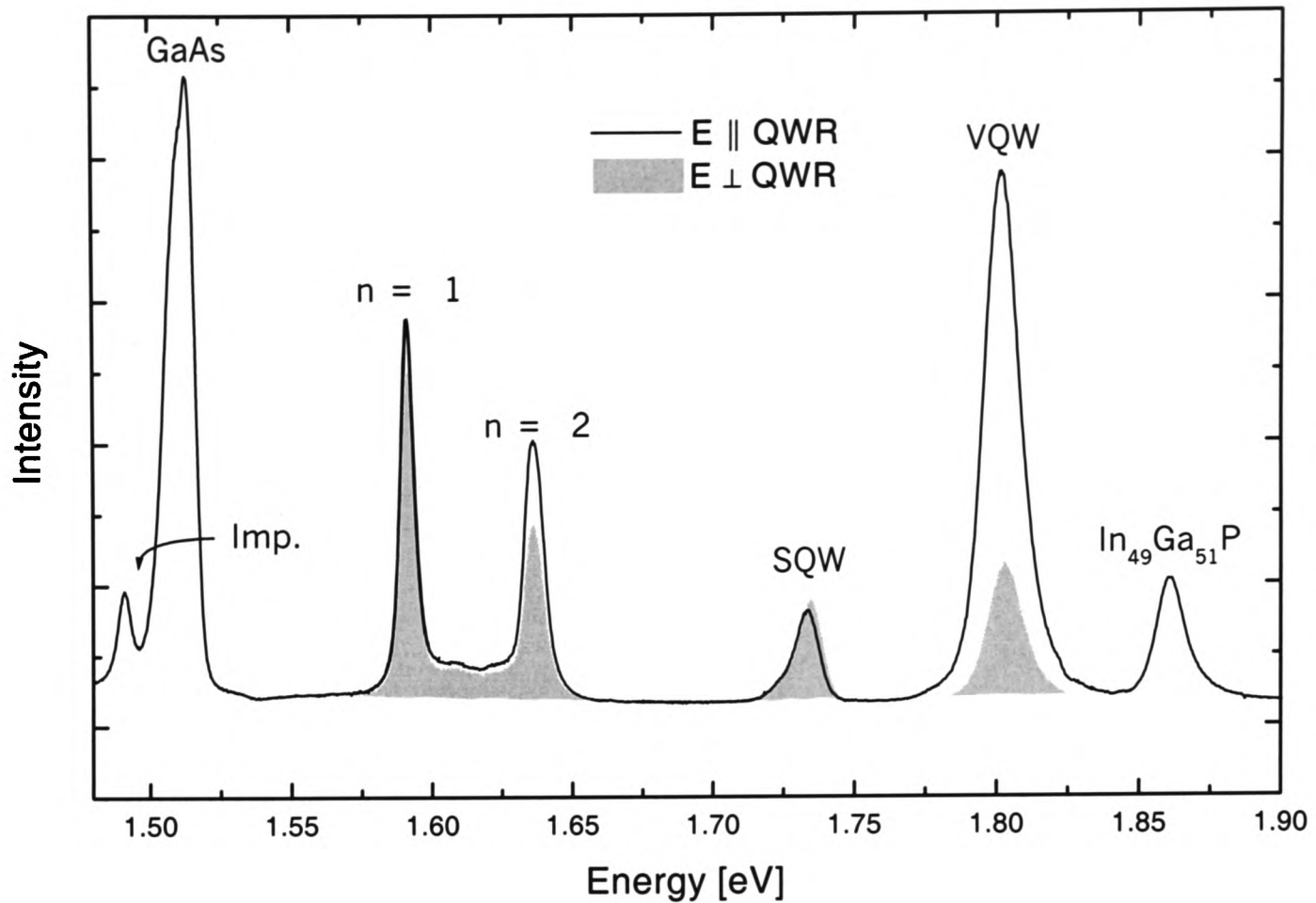


Figure 5.2: Photoluminescence spectrum of undoped sample B1. The two sharp excitonic peaks marked $n = 1$ and $n = 2$ originate from the quantum wire (QWR). Furthermore, transitions in the side (SQW) and vertical quantum well (VQW) can be observed, as well as the bulk material GaAs and $\text{In}_{49}\text{Ga}_{51}\text{P}$ capping layer. The depolarized spectrum is presented as grey areas.

excitation measurements discussed below confirm this assignment. The large subband spacing is consistent with the small wire dimensions.

The QWR peak widths are only 6 and 8 meV, and therefore document homogenous wires and high structural quality. In comparison with most other samples investigated in this work, but also in publications by other authors, the lines are well separated and are especially much sharper, i.e. exhibit a narrow linewidth (fig. 5.3) [Kapon 1992]. Compared to A1, sample B1 was processed with an improved fabrication process and grown in a newly installed MOCVD system which certainly improved the sample quality. Recent PL spectra by Oberli

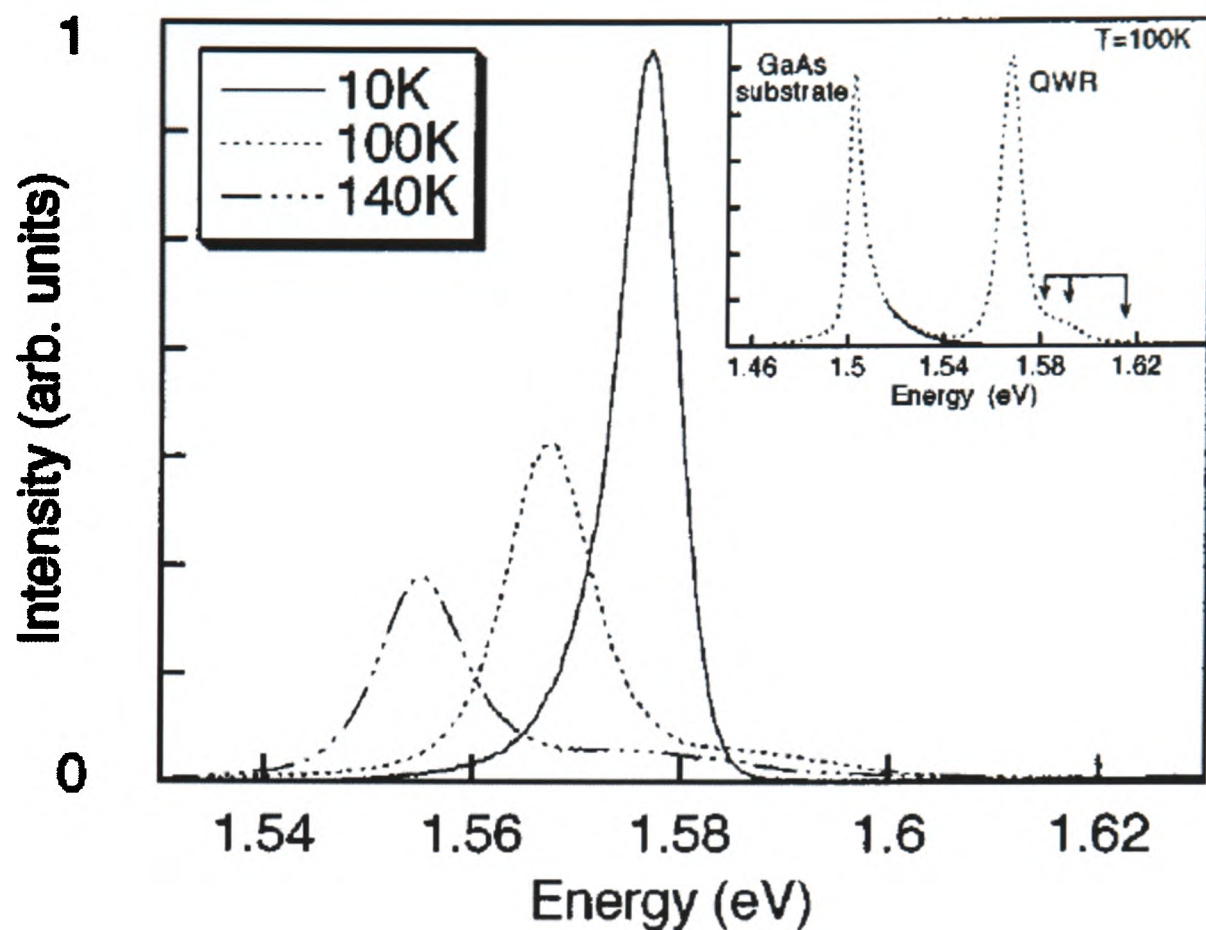


Figure 5.3: *QWR lines in time-integrated PL spectra at temperatures of 10, 100, and 140 K by Oberli et al. [1999].* PL for a sample with a nominal thickness of the GaAs layer of 2.5 nm shows a QWR luminescence linewidth of 8 meV, comparable to sample B1. The spectral shift of the QWR line is mainly caused by the temperature dependence of the GaAs band gap. Inset shows the full spectrum at 100 K (emission from thermally occupied excited states in the QWR is indicated by arrows).

et al. demonstrate similar achievements (fig. 5.3). However, the reliable reproduction of high quality samples is very difficult due to the high sophistication of the fabrication process.

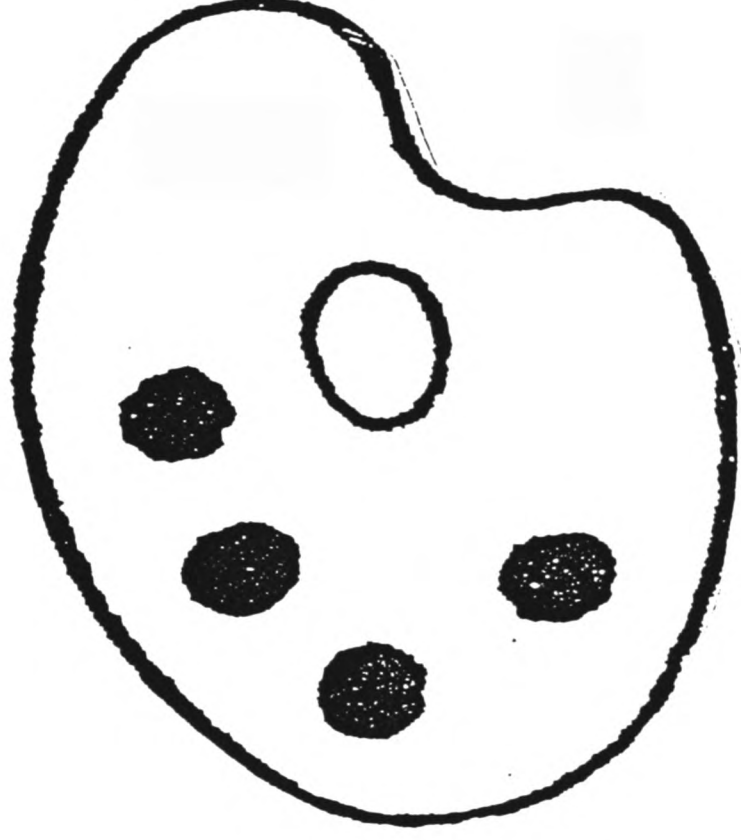
The strong luminescence from the second subband is unexpected. In section 5.5 PLE spectra indicate that a mechanism seems to slow down the carrier relaxation from the $n = 2$ level to $n = 1$ level, which would enhance radiative recombination from $n = 2$. Time-resolved measurements on these samples have shown that at 4 K the recombination time from $n = 2$ is twice as fast as from $n = 1$ [Hauert 2000]. Also PLE measurements will later discuss the relaxation processes in this sample (chapter 5.6).

To investigate the polarisation anisotropy of the QWR luminescence a polarising beam splitting cube was placed in front of the spectrometer slit. In a polarised spectrum the PL from the horizontally arranged QWRs is analysed horizontally, in a depolarised set-up the analyser is rotated by 90° . The $n = 1$ and 2 states show stronger intensities for a polarised spectrum (straight line) than for the depolarised one (grey area), while the PL intensity of the SQW does not display a significant difference. Polarisation anisotropy, which the QWR peaks exhibit can have a number of causes in semiconductor structures, such as physical strain, corrugated surfaces, uniaxial stress etc. [Bauer 1992]. However, the mixing of the valence bands at $k = 0$ in QWRs leads to a strong anisotropy in optical transitions, and is often considered a proof for two-dimensional confinement [Tsuchiya 1992, Coldren 1989, Weman 1992] (cf. chapter 2.4).

Cathodoluminescence (CL) measurements, which were performed by Till Rieman at Magdeburg University, Germany, show luminescence from the polycrystalline area on the (100) sample surface (fig. 5.4. e'). It seems that this recombination originates from fragmented GaAs well structures grown on the polycrystalline AlGaAs. The PL should have a broad linewidth and could result in the plateau seen between the two excitonic wire transitions. However, on the basis of near-field spectroscopy Hauert [2000] proposes that the plateau rather occurs due to recombination of QWR electrons in the lowest subband with excited hole states.

The PL peak at 1.804 eV seems to originate from the VQW. CL pictures show strong luminescence from the VQW region at this energy (fig. 5.4 b). The PL peak also shows a strong polarisation dependence, as it is expected for the VQW luminescence. This is comparable with the vertical quantum wells in T-shaped QWRs (cf. chapter 2.2), where the optical anisotropy is a well-known phenomenon observed in standard (001) quantum wells on the (110) cleaved surface [Akiyama 1996, Weman 1992]. However, it is not clear why the luminescence from the VQW is so strong. The carriers directly created in this Al-rich GaAs region, or trapped from the barrier material are expected to scatter rapidly into the QWR and

ORIGINAL IN COLOUR



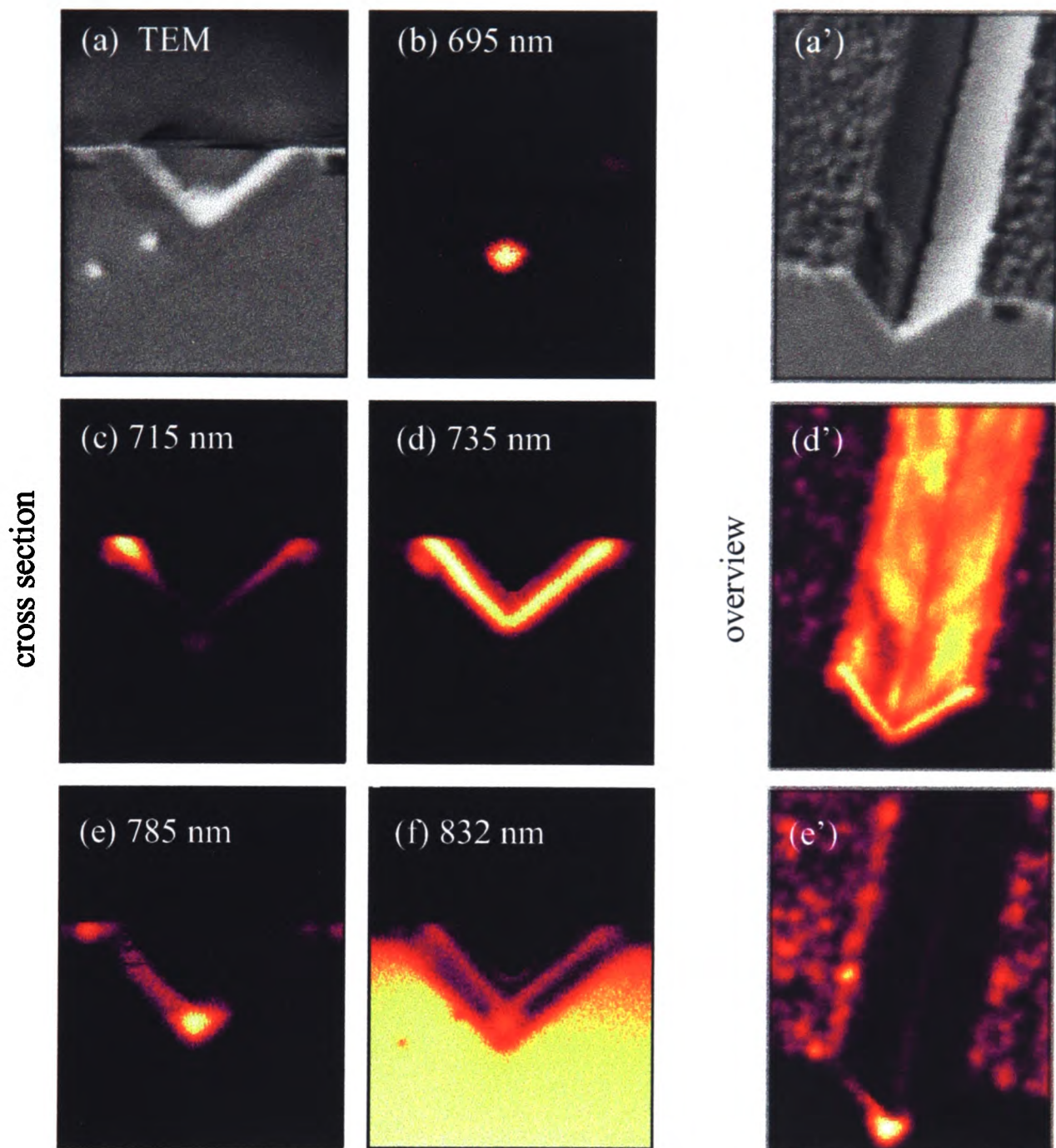


Figure 5.4: *Scanning electron microscopy (SEM) and cathodoluminescence (CL) pictures of undoped sample B1.* The pictures show in (a) and (a') cross-section and overview SEM pictures, respectively, in (b) CL from the VQW region, in (c) the top corner of side quantum well, in (d) and (d') cross-section and overview of the side quantum well, in (e) and (e') cross-section and overview of the quantum wire and in (f) GaAs.

contribute to the wire luminescence [Kiener 1996]. One reason could be the very large volume of the VQW, as its vertical length measures 380 nm. Possibly there is also non-

efficient trapping into the wire compared to relatively efficient radiative recombination in the VQW.

An alternative for the interpretation of the PL at 1.804 eV is the top corner of the SQWs. The abrupt end of the SQW at the top of the v-groove could create a local potential minimum and cause QWR-like states. This was observed in Poisson-Schrödinger simulations [O’Sullivan 2000] and can also be seen in CL pictures (fig. 5.4 (c)). However, this is rather unlikely, as the energies from the CL pictures do not match with the ones observed in PL spectra, and in overview CL pictures the corner states seem rather non-uniform along the wire direction. Nevertheless, PL from such states could also display polarisation dependence as they resemble quasi-1D structures and therefore lead to valenceband mixing at $k = 0$.

The peaks at 1.491 and 1.512 eV in the PL spectrum correspond to impurities – most likely carbon acceptors – and bulk GaAs, respectively. At 1.862 eV a single, sharp luminescence peak from the 20 nm $\text{In}_{49}\text{Ga}_{51}\text{P}$ capping layer can be observed.

Overall, the PL spectrum of Sample B1 demonstrates high structural quality of the QWR and a strong 2D carrier confinement, leading to large subband separations.

5.3 RESULTS FROM THE SCHRÖDINGER SOLVER

The identification of the two excitonic wire peaks in the PL spectrum of sample B1 so far has been made on the grounds of a simplified theoretical model and experimental indications. The application of the Schrödinger solver now delivers a convincing confirmation for the assignments of the wire peaks. From a cross-sectional TEM the profile of the v-groove QWR was derived and a computational area of 900 x 1000 nm including the neighbouring SQW and the VQW was chosen (fig. 5.5). Instead of the entire length of the SQW only a short section is considered for the simulation. Although this ignores parts of the real structure, investigations have shown that the difference is insignificant [O’Sullivan 2000]; the selection used has proven to show accurate results for the QWR states while

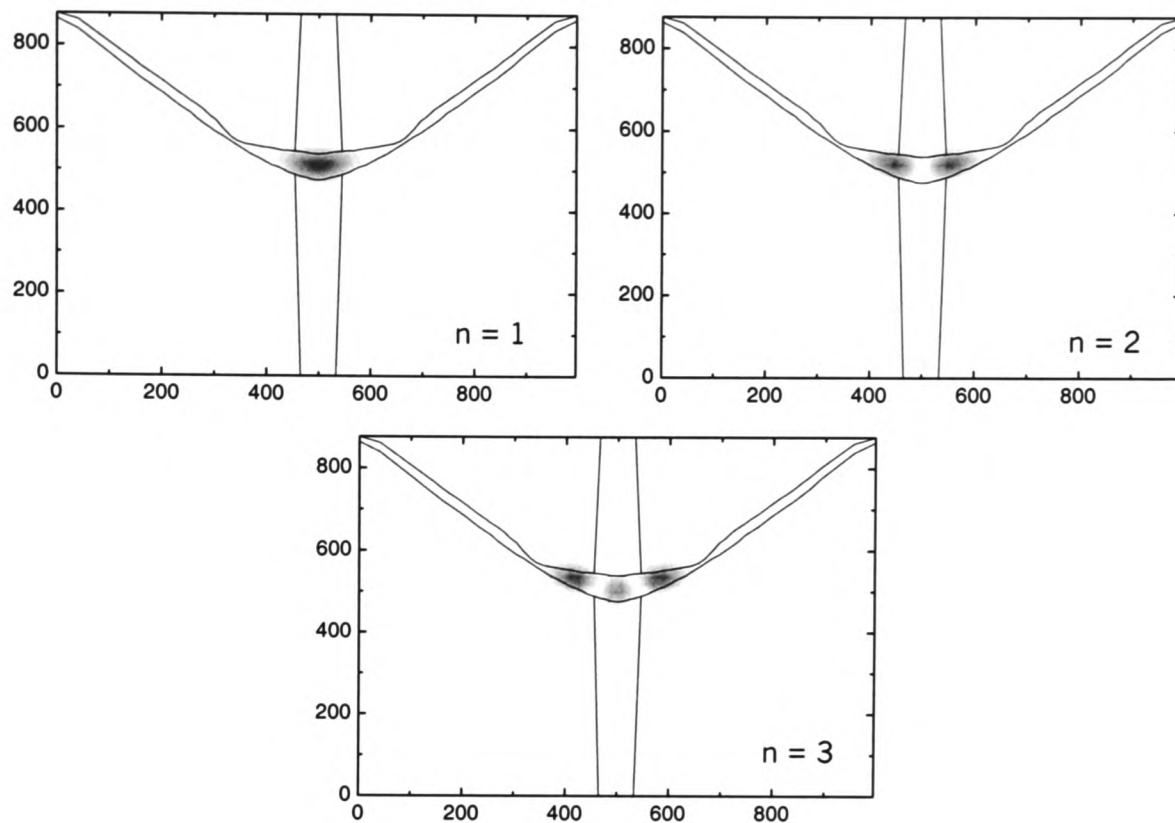


Figure 5.5: *Schrödinger solver calculations of probability distributions for undoped sample B1.* The selection contains the quantum wire, the side-quantum well and the vertical quantum well. The charge distributions for the first three confined states in the quantum wire are shown. The corresponding energies are shown in figure 5.6.

keeping the contribution from the SQW realistic. Furthermore, the restriction of the area improves the feasibility of the processor and memory intensive calculations substantially. The inclusion of the VQW takes into account the shift of the energy states in the QWR close to the vertical structure. A relative VQW potential of 75 % of the barrier band-gap offset has been found to lower the first QWR states by ca. 10 meV. The best agreements with experimental results were found for 85 % which corresponds to an Al-concentration of ~10 %. This is in reasonable agreement with the values (~16 %) obtained from EDX analysis for similar samples (cf. chapter 3.5).

Figure 5.5 shows the calculated wavefunction distribution for the first three confined states in sample B1. To obtain the transition energies as they appear in optical spectra both the confinement energies for electrons and holes have to be taken into account. For this the calculations of the Schrödinger equation for hole states were dealt with separately. For the sake of simplicity only heavy holes were considered and it was assumed that the holes reside in a parabolic band. The actual carrier effective masses were approximated by the values known from bulk.

The lowest electronic state in the centre of the QWR region is strongly localised. The second state is more delocalised and is shifted towards the pinch-off region. The shift is even stronger for the third level, although parts of the charge distribution also appears at the bottom of the QWR. Superimposing the resulting transition energies with the PL spectra in figure 5.6 demonstrates a strong agreement of theory with the experiment. It confirms that the peaks at 1.591 eV and 1.636 eV indeed correspond to optical transitions from the first and second electronic subband. A third subband does not appear in PL experiments, even for higher excitation powers, but can be seen in PLE spectra (chapter 5.6). To refine the numerical results further, the mixing of the valence band, many-body effects and the Coulomb interaction between electrons and holes will have to be included in the calculations.

5.4 OPTICAL TRANSITIONS IN APPLIED MAGNETIC FIELDS

To examine the optical transitions under an applied magnetic field, sample B1 was placed in a He-cooled superconducting magnet with fields up to 15.5 T (cf. chapter 4.5) and measured in three orthogonal configurations. The configurations are described in terms of the wire direction w (parallel to x), the direction of the magnetic field vector $\mathbf{B}$ and the wavenumber vector of the PL spectra k (parallel to z), which is equal to the growth direction.

Figure 5.7 shows the QWR PL spectra taken at varying magnetic fields in two configurations: the magnetic field perpendicular to the wire and sample surface, i.e.

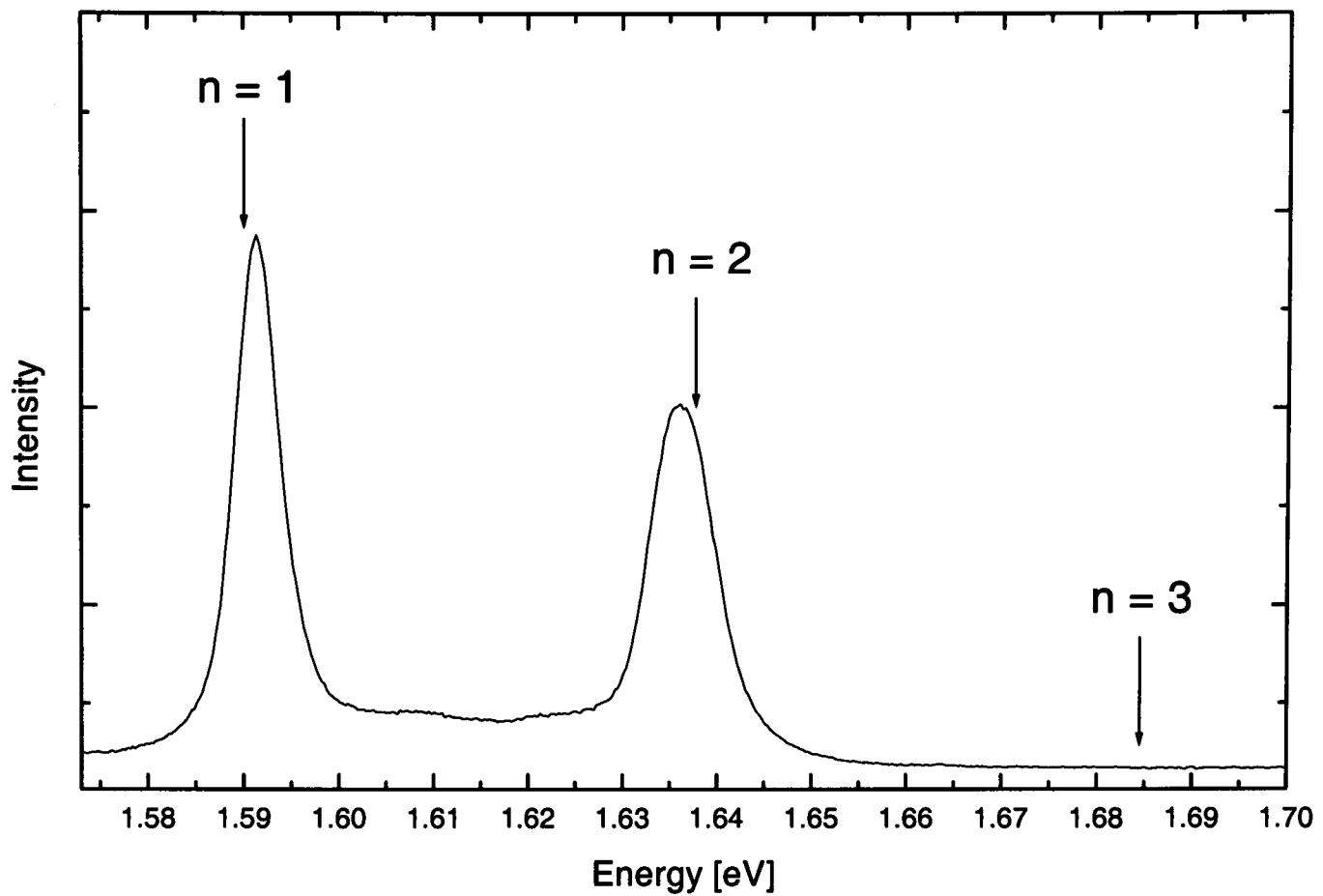


Figure 5.6. *Electronic subband energies of sample B1 calculated with the-Schrödinger solver. The three electron states shown in figure 5.4 are superimposed on the quantum wire PL spectrum and indicated by arrows.*

$w \perp B \parallel k$ (fig. 5.7 a) and parallel to the wire, i.e. $w \parallel B \perp k$ (fig. 5.7 b). When the field is applied perpendicular to the wire, a strong blue-shift can be observed for both subband levels, while the spectra taken with the field in the wire direction show only a small change up to 15.5 T.

The shift anisotropy is summarized in figure 5.8, where the peak positions for $n = 1$ (fig. 5.8 a) and 2 (fig. 5.8 b) are shown in dependence of the magnetic field and for all three orthogonal configurations. The linear Landau shift expected for bulk GaAs is shown as well as for reference. It is surprising, that the energy shifts of the $n = 1$ peak in the two configurations $w \parallel B \perp k$ and $w \perp B \perp k$ are negative up to 8 T. The analysis of the $n = 1$ peak indicated that the $n = 1$ peak might be a superposition of two peaks – possibly

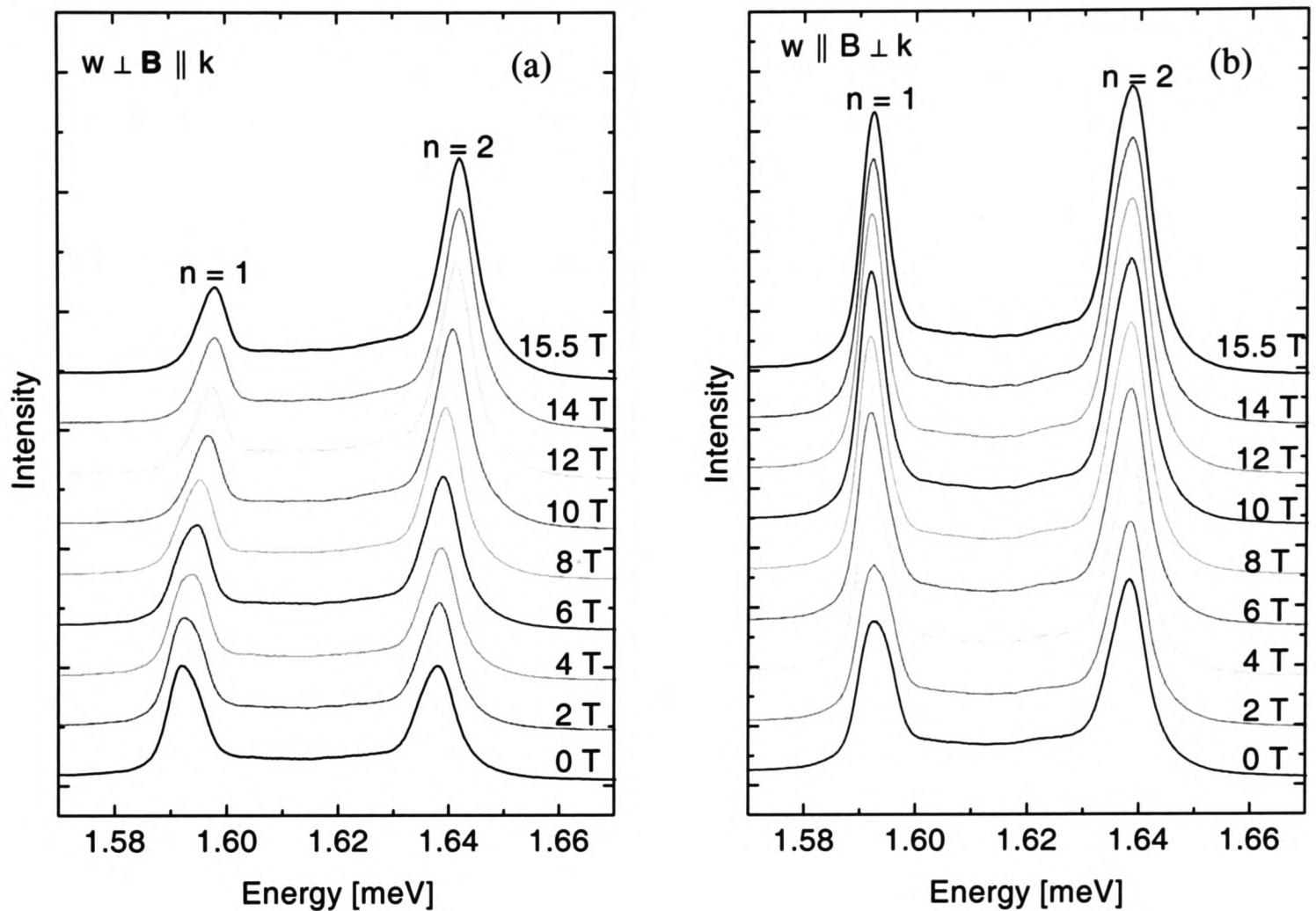


Figure 5.7: *Magneto-optical spectra of sample B1.* PL were taken with an applied magnetic field varying from 0 – 15.5 T. (a) shows the spectra with the **B**-field perpendicular to the wire. A blue-shift of the transition energies can be observed, while the spectra taken parallel to the wire (b) exhibit no significant change in energies.

recombination with different hole states. In this case the change of the relative intensities in favour of the lower energy peak could lead to believe that the energy shift is negative. However, this phenomenon is not adequately understood and therefore will be ignored for the following evaluation.

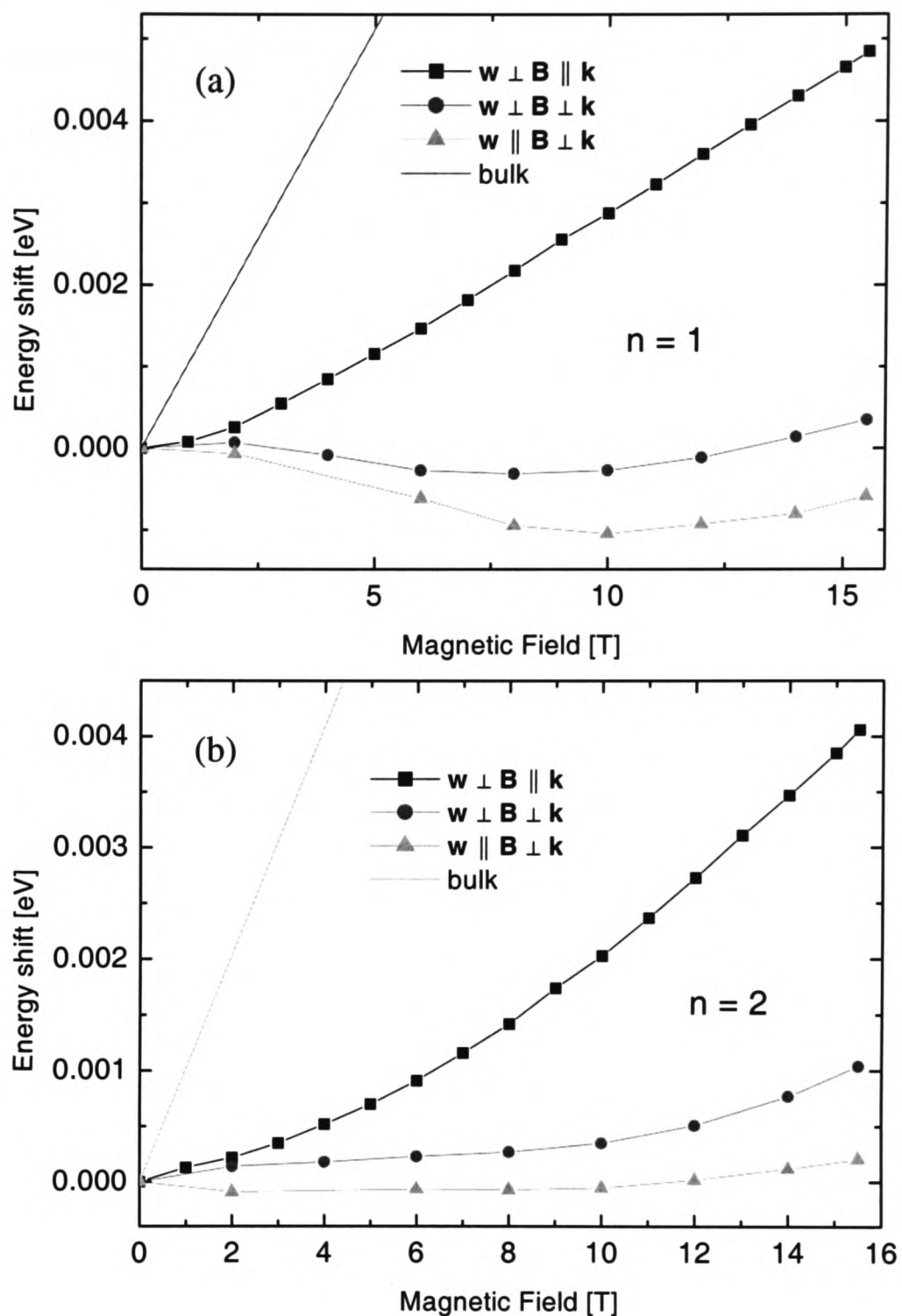


Figure 5.8: Energy shifts of $n = 1$ and 2 luminescence peaks with increasing magnetic field in three different configurations. The 2D confinement of the QWR leads to an anisotropy of the energy shifts. The shift is the strongest where the least confinement is felt by the exciton. The linear shift for bulk excitons is included as reference. The curves are all set to zero at 0 T.

In QWRs with an harmonic potential, such as the v-groove QWR (cf. chapter 2.5), the shift of the recombination energies for excitons are expected to be diamagnetic. The energy shift can be described as [Taguchi 1988]:

$$\Delta E_i(B) = \frac{4\pi^2 \hbar^4 \epsilon^2}{e^2 \mu \mu_j \mu_k} B_i^2, \quad i, j, k = x, y, z \quad (5.1)$$

where ϵ is the dielectric constant, e the charge of the electron, and the effective mass μ is defined as

$$\frac{1}{\mu} = \frac{1}{3} \left(\frac{1}{\mu_x} + \frac{1}{\mu_y} + \frac{1}{\mu_z} \right), \quad (5.2)$$

with μ_x , μ_y and μ_z the anisotropic reduced exciton masses. A diamagnetic change can be observed for most of the energies and the diamagnetic coefficients can be determined from parabolic fits. The coefficients for $n = 1$ were determined as $15.75 \mu\text{eV/T}^2$ for $w \perp \mathbf{B} \parallel k$ and for $n = 2$ as 16.6, 7.0 and $4.1 \mu\text{eV/T}^2$ for $w \perp \mathbf{B} \parallel k$, $w \perp \mathbf{B} \perp k$ and $w \parallel \mathbf{B} \perp k$, respectively (tab. 5.1). Subsequently, the effective masses can be calculated, which yields $\mu_x = 0.283 m_0$ for $n = 1$ and for $n = 2$ $0.298 m_0$, $0.125 m_0$ and $0.073 m_0$ for μ_x , μ_y and μ_z and $\mu = 0.120 m_0$.

The anisotropy of the diamagnetic energy shifts reflects the 2D confinement of the QWR states. In the case of the $\mathbf{B}$ -field in wire direction the exciton experiences the lateral *and* the quantum well confinement, for which the excitons has the largest effective masses. It therefore exhibits the smallest shift. When the magnetic field is perpendicular to the sample surface ($w \perp \mathbf{B} \parallel k$) there is only the relatively weak lateral confinement and the energy shift is large. This is consistent with observations by Nagamune et al. [1992] (table 5.1), Rinaldi et al. [1994a, b] and Steer et al. [1998].

The energy shift anisotropy can also be considered as a result of different exciton Bohr radii.

Nagamune et al. calculated the radii for the three different directions using the relation

$$a_0 = \frac{4\pi\hbar^2\epsilon}{e^2\mu_i}, \quad (5.3)$$

NAGAMUNE 1992	Energy shift $\Delta E_i/B^2$ [$\mu\text{eV}\text{T}^2$]	Effective mass μ_i [m_0]	Bohr radius a_{0i} [nm]
i			
x	16.3	0.293	2.4
y	7.0	0.126	5.5
z	4.5	0.081	8.6
$\mu = 0.127 m_0$		$E_b = 10.1 \text{ meV}$	

SAMPLE B1 $n = 2$	Energy shift $\Delta E_i/B^2$ [$\mu\text{eV}\text{T}^2$]	Effective mass μ_i [m_0]	Bohr radius a_{0i} [nm]
i			
x	16.6	0.298	2.3
y	7.0	0.125	5.6
z	4.1	0.073	9.6
$\mu = 0.120 m_0$		$E_b = 9.57 \text{ meV}$	

BULK	Energy shift $\Delta E_i/B^2$ [$\mu\text{eV}\text{T}^2$]	Effective mass μ_i [m_0]	Bohr radius a_{0i} [nm]
i			
x, y, z	103.9	0.059	11.8
$\mu = 0.059 m_0$		$E_b = 4.7 \text{ meV}$	

Table 5.1: Summary of energy shifts, effective masses, Bohr radii and-excitonic binding energies. The values calculated from magneto-optical-experiments by Nagamune et al. [1992] are shown in comparison with the-results for sample B1 ($n = 2$). The values for bulk are listed for reference.

and concluded that the excitons are anisotropically shrunk, i.e. have a smaller radius in wire direction (2.4 nm) than perpendicular to it (5.5 and 8.6 nm). The radii determined for the $n = 2$ state in sample B1 are shown in table 5.1 and show a good agreement with the values obtained by Nagamune for a comparable v-groove QWR with $\sim 20 \times 10$ nm cross-section.

Finally, the exciton binding energy can be obtained using the relation

$$E_b = \frac{e^4 \mu}{32\pi^2 \hbar^2 \epsilon^2}. \quad (5.4)$$

This yields $E_b = 9.57$ meV for the $n = 2$ exciton, which is slightly smaller than 10.1 meV measured by Nagamune for a ground state exciton. This can be understood in terms of the spatial extent of the states. As seen in the Schrödinger calculations in section 5.3 the first state is localised in the centre of the QWR whereas the second state is delocalised and shifted towards the pinch-off region. The delocalised wave function has a larger average correlation length for the relative motion of the electrons and holes, which results in a reduction of the exciton binding energy and leads to a larger diamagnetic shift. As it can be seen in the calculated carrier distribution functions, especially the Bohr radius for the direction z is expected to be larger in the $n = 2$ case than $n = 1$. In fact, as it can be seen in table 5.1, the largest difference between the radii measured by Nagamune and obtained from sample B1 occurs for a_{0z} .

The curves exhibit a non-parabolic component, especially at high magnetic fields (> 10 T). When the exciton or the cyclotron radius becomes much smaller than the width of the confinement potential the energy shifts become linear (Landau shift). But also a non-parabolicity of the potential or a larger than expected free carrier contribution could cause a cross-over to linear shifts.

In figure 5.9 the effect of a magnetic field on PL originating from the SQW, the VQW and the 20 nm $\text{In}_{49}\text{Ga}_{51}\text{P}$ capping layer are shown. For all peaks an energy shift anisotropy of different degrees can be observed which can be explained by the geometry of each structure. The SQW and the capping layer which are parallel to each other, show the smallest shift, when the B-field is in the wire direction, as an exciton is strongly confined by the quantum well. In the $w \perp \mathbf{B} \parallel k$ and the $w \perp \mathbf{B} \perp k$ configurations the exciton is less confined and therefore the shifts are stronger and should be similar as the B-field penetrates the (111) quantum wells almost at an perfect 45° angle. The VQW is expected to show small, identical

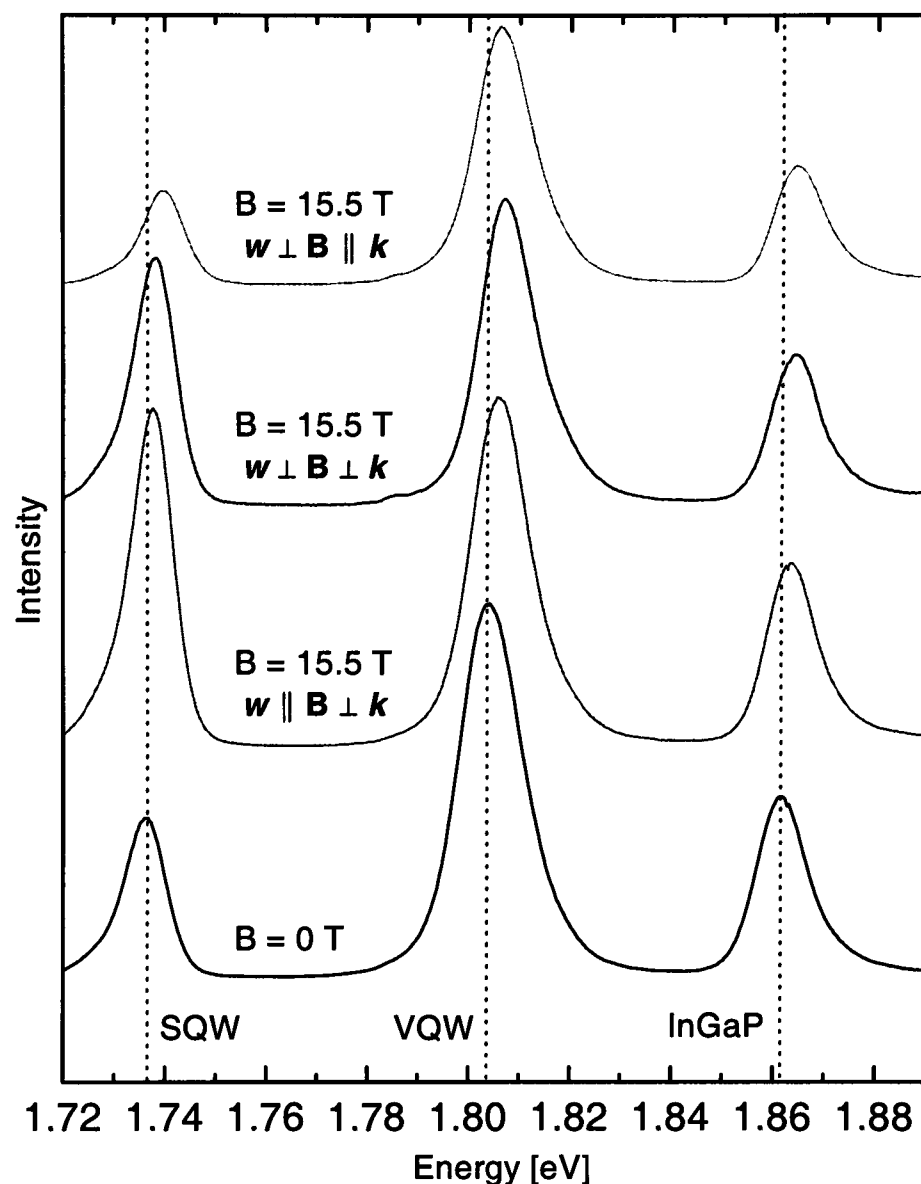


Figure 5.9: Energy shifts of side quantum well (SQW), vertical quantum well (VQW) and bulk InGaP luminescence peaks in an applied magnetic field.- The SQR peak shifts the strongest when the B-field is perpendicular to the sample surface ($w \perp B \parallel k$) and VQW peak in the $w \perp B \perp k$ case. The shifts of the peak from the InGaP capping layer are isotropic. The dotted lines are guides to the eye.

shifts whenever the B-field is in plane, i.e. $w \perp B \parallel k$ and $w \parallel B \perp k$ and the largest shift should occur when the B-field is perpendicular to the quantum well, i.e. $w \perp B \perp k$. This can

be confirmed by the measurements: The shifts for $w \perp B \parallel k$, $w \parallel B \perp k$ and $w \perp B \perp k$ are 2.7, 2.4 and 3.9 meV.

In conclusion, the results from the MPL show strong indications for the excitonic character of the recombination. The strong 2D confinement in the QWR is shown and in agreement with the works of others the excitons exhibit anisotropic shrinkage. Also the peak assignment of the SQW, VQW and capping layer are confirmed by the characteristic energy shift anisotropies. However, some more work is needed in order to understand the negative energy shifts occurring in the $n = 1$ PL spectra.

5.5 HIGH EXCITATION POWER EXPERIMENTS

To investigate the dependence of the optical properties on increased carrier concentrations spectra of sample B1 were taken with a series of different excitation powers varying over several orders of magnitude (fig. 5.10). At low intensity the spectrum is strongly excitonic, and the free carrier recombination is weak. With increasing excitation power the lines broaden and there is a distinct, systematic reduction in the relative intensity of the $n = 1$ exciton, and a higher energy wing develops which extends to the $n = 2$ line. At 10 mW the recombination from the lowest level is very weak and the luminescence from $n = 2$ has decreased, too, but remains as the dominant feature in the spectrum.

The fact that transition energies do not shift underlines the excitonic nature of the transitions and that band-gap renormalization (BGR) is very small as seen also by Ambigapathy et al. [1997] in v-groove QWRs⁴. The decrease of the $n = 1$ signal, however, is not expected and has not a straightforward explanation [van der Meulen 1998]. The behaviour is qualitatively

⁴ The issue of BGR in 1D is still controversially discussed. Hu and Das Sarma [1992] have calculated the BGR in QWRs and Cingolani et al. have reported the measurement of BGR in quantum well wires. However, Amigapathy et al. [1997] have found evidence that no measurable BGR is observed in QWRs. The time-resolved measurements in chapter 8 also show no indication of a BGR in the investigated samples.

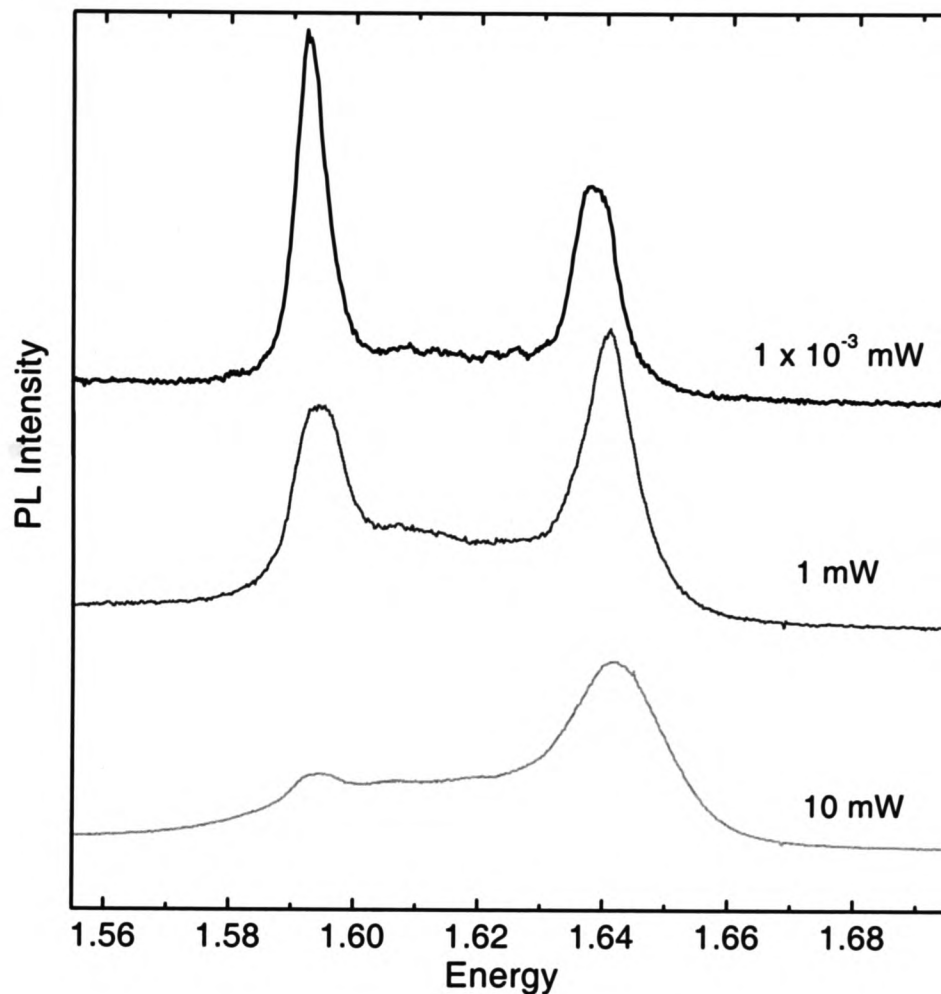


Figure 5.10: *Quantum wire luminescence of undoped sample B1 in-dependence of excitation power. Increasing the excitation power leads to a-decrease of the luminescence from the $n = 1$ level, which might be due to-Coulomb correlation effects.*

similar to the results of a theoretical model proposed first by Ogawa and Takagahara [1991] and applied to v-groove QWRs by Rossi and Molinari [Rossi 1996a, 1996b]. They have calculated optical absorption spectra of v-groove QWRs at increased carrier concentrations taking the Coulomb correlation between electrons and holes into account. In comparison to the free carrier case the Coulomb correlation leads to two major differentiating

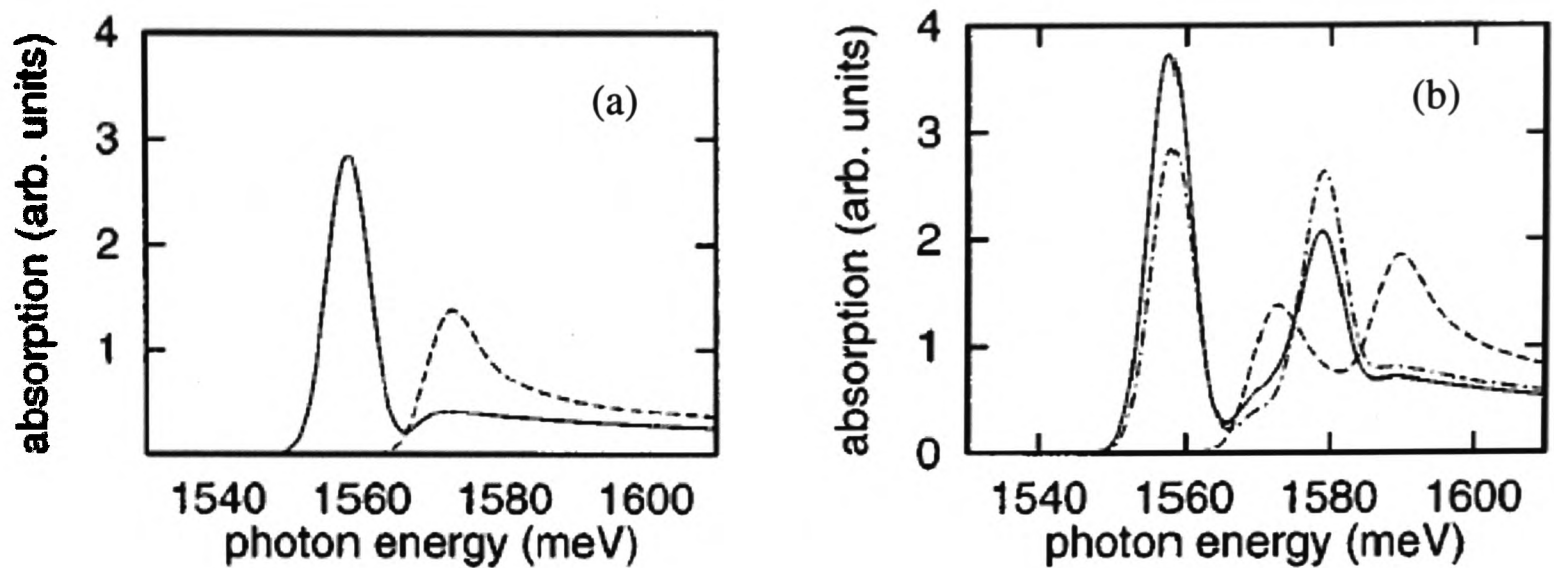


Figure 5.11: *Calculated absorption spectra of v-groove quantum wires (QWR) with and without Coulomb correlation effects [Rossi 1996a, b].* The absorption spectra show the results of a free carrier (FC) model (solid curve) and an electron-hole Coulomb correlation model (dashed curve) for a QWR, taking the lowest (a) and two lowest subbands (b) into account. The dash-dotted curve in (b) illustrates the neglecting of the intersubband coupling.

characteristics. Firstly, a pronounced excitonic peak can be observed below the band-gap⁵, and secondly, the 1D band edge singularity is strongly suppressed (fig. 5.11 a). The suppression of the singularity is due to an effective electron-hole “repulsion” which strongly decreases the relative oscillator strength for the Coulomb correlation case compared to the free carrier case. This effect is larger close to the band edge.

With increasing carrier densities the excitonic absorption is reduced due to phase space filling and screening of the attractive electron-hole interaction (fig. 5.12 a) and above the Mott density the exciton disappears completely. Rossi and Molinari also investigated the role of higher subbands and found that the reduction of the excitonic absorption at higher carrier

⁵ For a v-groove QWR with 10 nm thickness in the centre of the groove and no pinch-off region the calculated binding energy of the exciton is 12 meV.

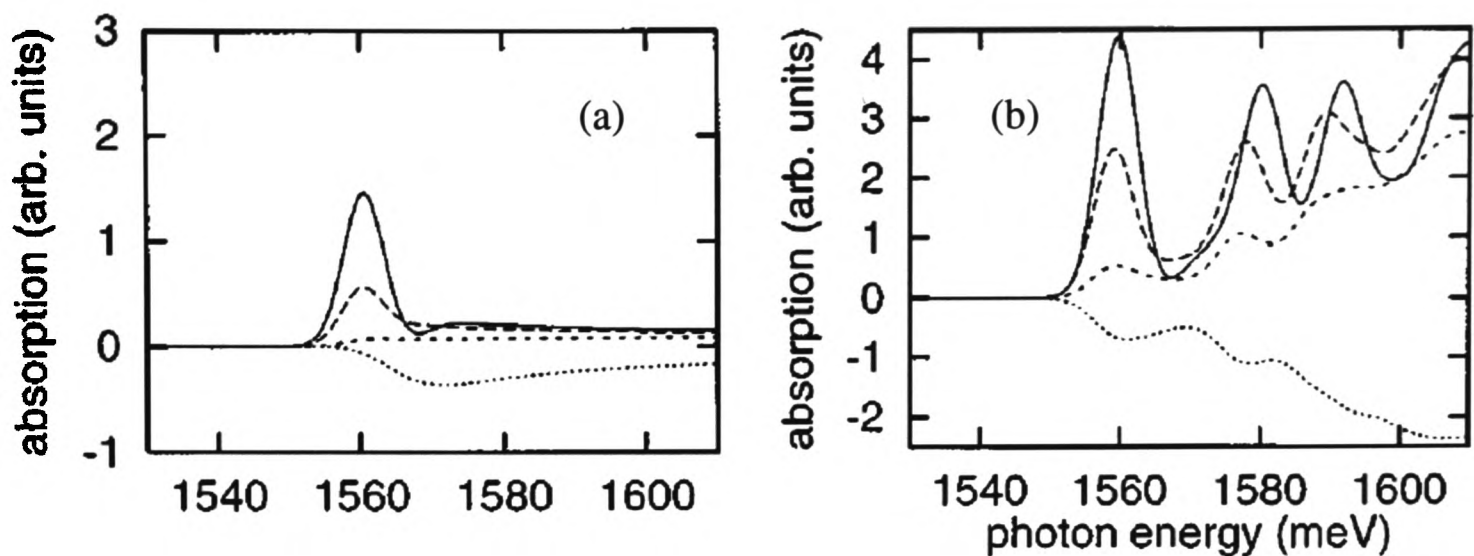


Figure 5.12: *Calculated absorption spectra for increasing excitation power including screening and phase-space filling effects [Rossi 1996a, b]. (a)- shows the case for one subband. With increasing excitation power the intensity decreases. A realistic 12 subband model is shown in (b).*

concentrations applies also to higher subbands (fig. 5.12 b). Additional to the suppression of the 1D singularities, also an intersubband coupling contributes to the decrease. However, the effect on the higher subbands is not as strong as on the lowest level and a reversal of the relative intensities with increasing carrier densities, as seen for sample B1, can also be similarly observed in the calculated spectra.

A comparison of the estimated carrier densities from the experiments and ones used for the theoretical calculations can give some idea in how far the theoretical model reflect the results of the experiments. To calculate linear carrier densities, first the number of photons in the incident laser beam has to be estimated, which can be derived from the laser power P and the laser energy $\hbar\omega$. Then the volume in which the photons are absorbed has to be determined to obtain the number of photogenerated electrons. In QWRs the volume is not only defined by the laser spot A , but also by the dimensions of the wire, i.e. the wire width L_y and thickness L_z . The carrier density can then be calculated as

$$n_e = P/\hbar\omega \times \gamma L_z L_y / A, \quad (5.1)$$

The spectrum taken at the lowest power (1×10^{-3} mW) corresponds to a carrier density of $n_e \sim 1 \times 10^6 \text{ cm}^{-1}$. At this density the theoretical calculation still shows a strong $n = 1$ peak. At the highest density of 10 mW a carrier density of $n_e = 1 \times 10^{10} \text{ cm}^{-1}$ can be estimated, which in the model leads to a strongly reduced $n = 1$ peak. The comparison of the carrier densities indicates that the overall effect on high excitation powers in sample B1 can roughly be understood in terms of Rossi's model. To evaluate the data more quantitatively the calculation of emission spectra would be beneficial.

5.6 PHOTOLUMINESCENCE EXCITATION SPECTRA

A direct way to probe and analyse the band structure of a semiconductor optically is to use absorption spectroscopy. However, this technique is performed in transmission geometry where samples have to be thin enough to transmit sufficient light for detection. In the case of v-groove QWRs it would involve the delicate process of thinning the samples which are put at risk of being jeopardized. To circumvent this technological issue PL excitation (PLE) experiments, done in reflection geometry, can be used to obtain information about the absorption in semiconductors structures. With the use of a tuneable dye laser (c.f. chapter 4.6) the emission intensity at a fixed wavelength – typically set at the high energy side of an emission line – is recorded as a function of the excitation photon energy. This results in a spectrum which is roughly equivalent to an absorption spectrum.

Figure 5.13 shows the PL and PLE spectra of sample B1 taken at different temperatures with a dye laser (1.78 eV, 1 mW). In (a) the PL spectrum shows the luminescence from the first two QWR levels as well as the SQW. With increasing temperature the $n = 2$ and SQW PL intensities decrease and broaden partly due to increasing non-radiative recombination and phonon scattering. Thermal decrease of the band-gap energy leads to the red-shift of the energies. In contrast, the PL from the lowest QWR state, increases in temperature first and

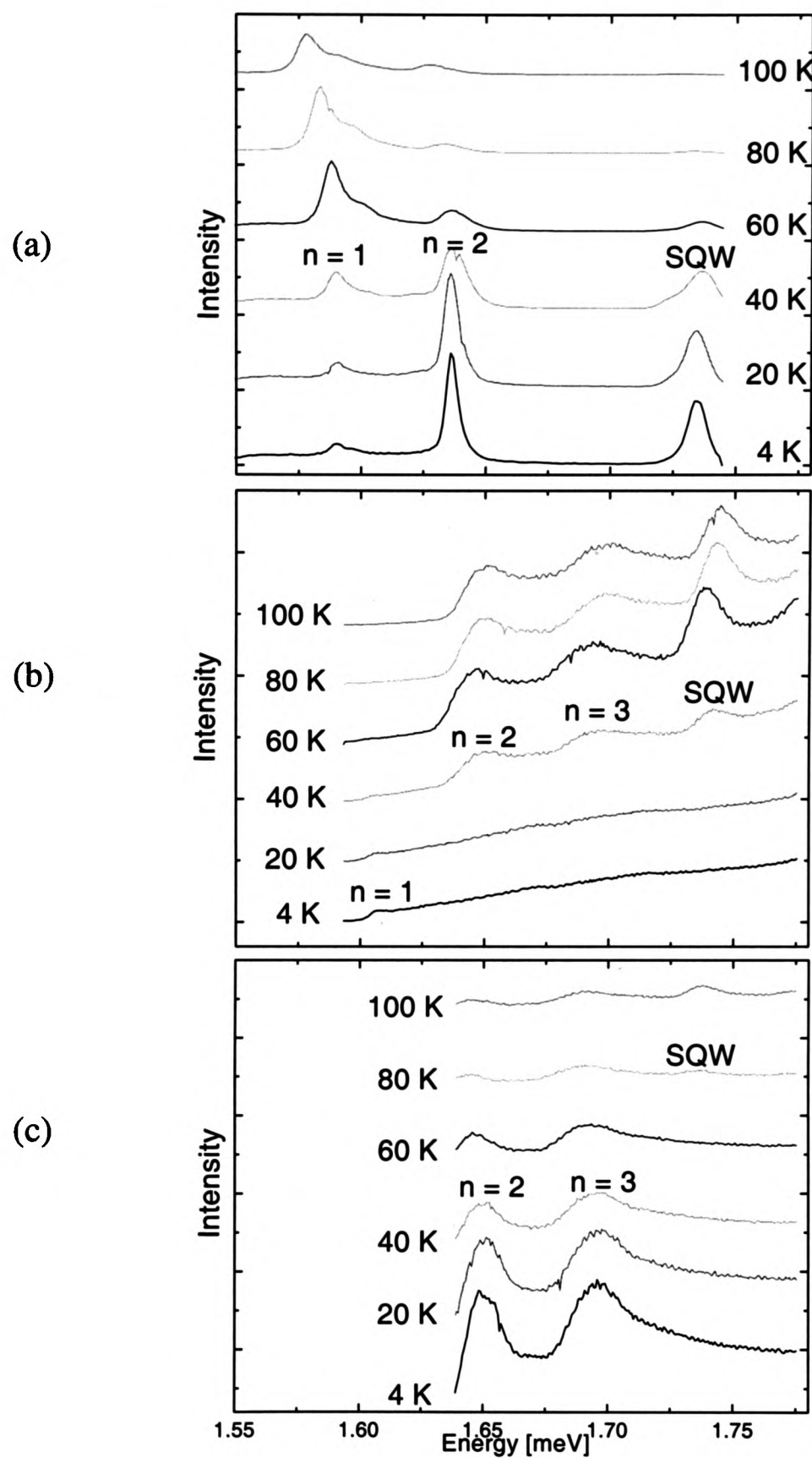


Figure 5.12: Photoluminescence (a) and photoluminescence excitation (PLE) spectra (b, c) of sample B1. At low temperatures only the excitonic transition at $n = 1$ is visible in the PLE spectrum. Higher electron states only emerge at higher temperatures indicating a mechanism inhibiting intersubband transitions.

decreases and broadens only above 80 K. It should be noted that the strongest changes in intensities for all peaks occur between 40 and 60 K.

The PLE measurements give an insight into what seems to be an inhibited intersubband carrier relaxation at low temperatures⁶. In the 4 K spectrum taken at $n = 1$ a small excitonic peak from the lowest subband can be observed at 1.607 meV, but none from higher subbands, indicating a negligible carrier relaxation from higher levels. When the temperature is raised the $n = 1$ exciton peak washes out, as expected, and disappears at around 40 K. Surprisingly, at about the same temperature, peaks appear at energies which correspond to excited QWR states, as calculated by the Schrödinger solver (cf. chapter 5.3), and the first SQW state. Over the next 20 K the intensities increase dramatically and are persistent up to 100 K. These contributions to the $n = 1$ luminescence result in the sudden increase of the $n = 1$ peak in the PL spectrum between 40 and 60 K.

The origin for this behaviour is not entirely clear yet, but there seems to exist a mechanism, which inhibits the carriers to relax efficiently from higher energy levels into the $n = 1$ subband at low temperatures. At 40 K this inhibition is lifted and carriers from excited QWR states can relax efficiently into the lowest subband. One possibility is that the $n = 2$ states, which are confined in the narrow pinch-off region, are localised due to interface roughness. Such localised excitons in v-groove QWRs have been studied by e.g. Tribe et al. [1998], Lomascolo [1998] and Oberli et al. [2000]. Wang et al. [1997] have observed large Stokes shift of the transition from the first excited electron into the first excited hole state and have attributed it to strongly localised excitons. The Stokes shift of the excited exciton was observed to be much stronger than for the ground state and was explained by larger structural inhomogeneities of the (311)A than the (100) facets. The Stokes shift for the $n = 2$ peak of sample B1 is large (~13 meV) and could therefore indicate inhomogeneities. Then

⁶ All PLE spectra are shown on the same scale to be comparable across spectra with different detection wavelengths.

the relaxation of localised carriers in the excited state into the ground state would be slow and the radiative recombination rate would be strong. However, at 40 K the thermal energy could be sufficient to thermally excite and delocalise carriers and increase the relaxation rate from $n = 2$ into $n = 1$.

This is consistent with the PLE spectra taken at the energy of the $n = 2$ exciton, where the temperature dependence of the peak intensities is reversed. At 4 K the carriers from the third subband relax into the second subband where they eventually recombine due to the poor relaxation efficiency into the $n = 1$ subband. This would explain the appearance of the $n = 2$ exciton in the low-temperature PL spectrum. When the temperature is increased the intensities decrease and at 100 K the spectrum only shows remnants of the peaks. This is due to the increased relaxation efficiency into the lowest subband. As a result, the $n = 1$ luminescence increases with higher temperature and the $n = 2$ luminescence washes out. This transition can be observed particularly between 40 and 60 K.

5.7 CONCLUSIONS AND OUTLOOK

The results of various optical experiments have demonstrated the successful fabrication of undoped v-groove QWR. The most important findings can be summarised as follows:

- An improved fabrication process, as optimised photolithography exposure and development times, has led from samples (A1) with broad PL linewidths of 30 meV to samples (B1) with linewidths as narrow as 6 meV, attesting to high structural quality and an uniform wire thickness.
- Calculations from the Schrödinger solver show good agreement with the experimental results and confirm the assignment of the two excitonic wire peaks in sample B1. However, including the valence band mixing, many-body effects and the Coulomb interaction between electrons and holes would improve the accuracy of the solutions.

- In applied magnetic fields the anisotropy of energy shifts of optical transitions confirms the 2D confinement in the QWR. In agreement with the observation of Nagamune et al. [1992] a shrinkage of the excitons can be established. A binding energy of 9.4 meV was derived for the $n = 2$ exciton.
- Sample B1 shows suppression of the excitonic recombination at high excitation powers due to screening of the electron-hole interaction and phase space filling.
- Inefficient relaxation from excited subbands into the lowest subband at low temperatures lead to the appearance of the $n = 2$ exciton in PL spectra of sample B1. PLE measurements reveal that at higher temperatures the relaxation process becomes more efficient and leads to an increase of the $n = 1$ PL peak intensity above 40 K.

CHAPTER 6

OPTICAL PROPERTIES OF MODULATION-DOPED V-GROOVE QUANTUM WIRES

CONTENTS

6.1	INTRODUCTION	87
6.2	ELECTRONIC STATES IN MODULATION-DOPED SAMPLES	88
6.3	MAGNETO-OPTICAL EXPERIMENTS	103
6.4	MAGNETO-TRANSPORT EXPERIMENTS	109
6.5	CONCLUSIONS AND OUTLOOK.....	112

6.1 INTRODUCTION

The considerable interest which has emerged recently in producing and investigating 1D electron gases (1DEGs) originates from the remarkable success in achieving a detailed understanding of 2D electron systems. This was possible through the fabrication of modulation-doped quantum wells which has led to the realisation of high mobility 2DEGs. One of the most successful methods to produce 1DEGs so far has been the split-gate technique. It uses an electric field applied through gates on high quality 2DEGs depleting certain areas to obtain an 1DEG [Thornton 1986, Thomas 1996]. However, as the gates are fabricated with photolithography the dimensions of the contacts depend on the relatively poor resolution ($\sim 1 \mu\text{m}$) of the mask aligner resulting in very small lateral confinement energies ($\sim 1 \text{ meV}$). The samples are also not suited for optical spectroscopy as the valence band holes are not confined. QWRs fabricated from reactive ion etched [van Houten 1987, Menshig 1990] or ion bombarded [Calleja 1991] modulation-doped quantum wells on the other hand suffer from surface damage and sidewall depletion as well as weak lateral confinement.

Modulation-doped v-groove QWRs promise to provide 1DEGs with strong 2D confinement and high optical quality. However, there has hardly been any work on doped v-groove QWRs to date [Sa'ar 1996, van der Meulen 1998, Steer 1998]. To the knowledge of the author the following chapters will therefore present the first systematic work on modulation-doped v-groove QWRs. The effect of doping on the optical properties have been studied by PL, CL and magneto-PL and will be related to the results obtained from the Poisson-Schrödinger solver and the undoped samples described in chapter 5. In particular doped samples A2, B2 and B3 can be directly compared to the undoped samples A1 and B1, respectively, as they were grown with nominally identical growth parameters, except for the dopant layers.

In some samples the measurements indicate the presence of a degenerate Fermi system and free carrier behaviour and even the theoretically expected Fermi edge singularity (FES) was observed. Hence, these results demonstrate the successful development of modulation-doped v-groove QWRs. As the interest in doped semiconductor structures partly originates from the expectation of improved electrical properties, some magneto-transport measurements performed on related samples by the collaborating group in Jülich, namely A. Schwarz [Schäpers 1997, Schwarz 1999], will complement the results. The FES is a major feature of this work and will be elaborated on in chapter 7.

6.2 ELECTRONIC STATES IN MODULATION-DOPED SAMPLES

The samples discussed in this section have been developed in several stages. The first doped samples C and D show indications of successful doping, however they also exhibit relatively small confinement energies and broad linewidths, reflecting poor structural quality. To examine alternative Al-sources for the growth of the barrier material AlGaAs, sample E was fabricated using a DMMAI source instead of the usual TMAI. Sample A2 is related to undoped sample A1 (cf. chapter 5) and shows a stronger 2D confinement than samples C and D with up to three occupied subbands due to doping. The latest generation of samples includes B2 and B3, which show large subband separations and narrow linewidths indicating high structural quality. They were fabricated in a set with sample B1 described in chapter 5. All the following PL spectra were obtained using argon laser excitation at 2.4 eV, well above the band-gap of $\text{Al}_{30}\text{Ga}_{70}\text{As}$, the confining barrier and the samples were kept at 7 K in a He-flow cryostat, unless stated otherwise.

(a) Samples C and D – Polarisation anisotropy and excitation power dependence

Sample C has a nominal GaAs quantum well thickness of 10 nm and the 3.5 nm (5 nm) thick upper (lower) dopant layer has a Si-concentration of $2 \times 10^{17} \text{ cm}^{-3}$. The QWR thickness and

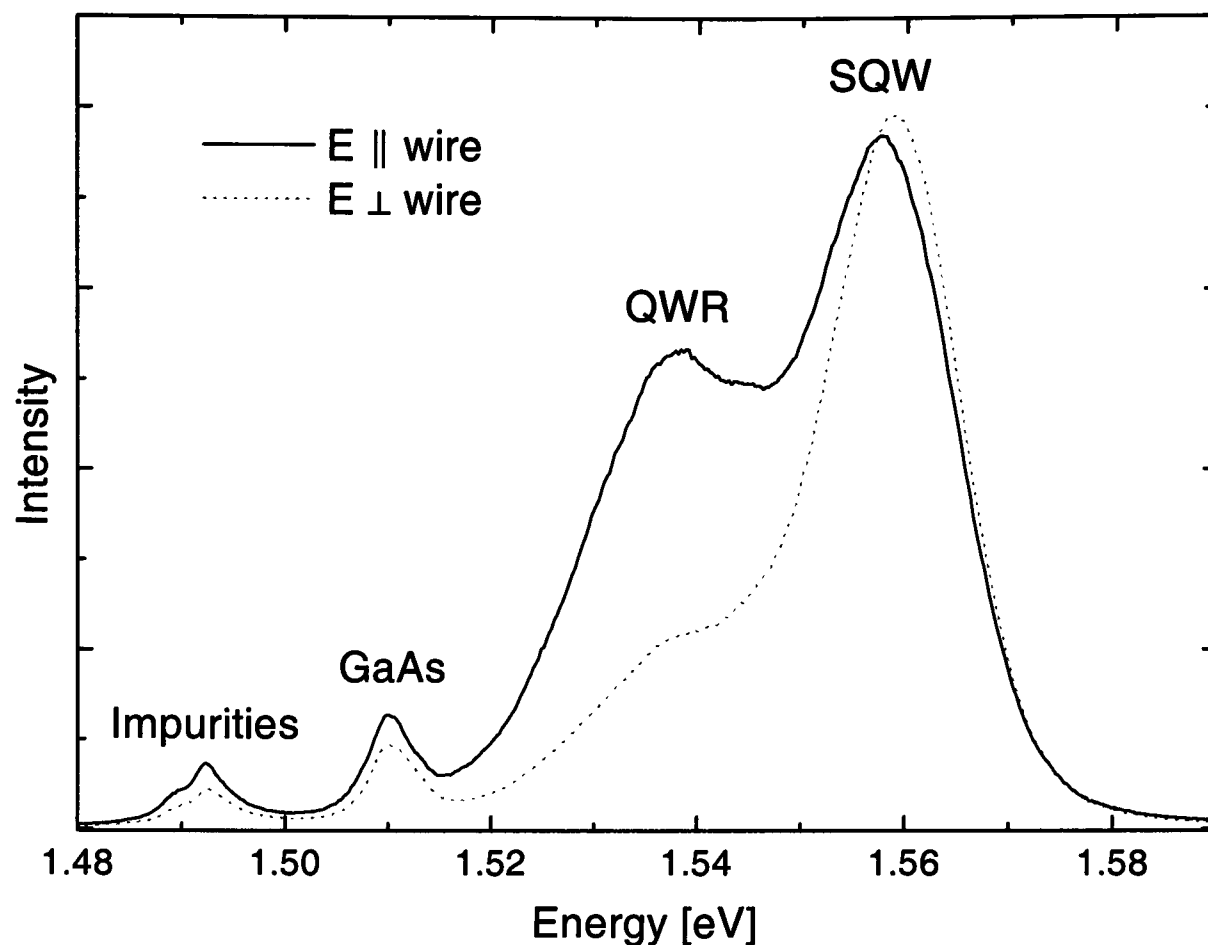


Figure 6.1: Photoluminescence spectrum of sample C. The quantum wire shows strong a polarisation anisotropy. No significant polarization-dependence can be observed for the side quantum well (SQW), bulk GaAs- and impurities peaks.

width were determined in TEM pictures as 18 nm and 50 nm, respectively. The PL spectrum for sample C in figure 6.1 shows the peaks corresponding to carbon impurities, bulk GaAs, the QWR and the SQW. The recombination energy of the SQW is consistent with the energy of a 10 nm thick *undoped* quantum well, which yields 1.56 eV. The assignment of the QWR can be made on the grounds of the peak position relative to the SQW; the QWR is almost two times thicker and the recombination is therefore expected to be lower in energy than the SQW. But also the polarisation dependent measurements support the assignment. As discussed in chapter 2.4, the QWR should exhibit a polarisation anisotropy due to valence band mixing at $k=0$, while the intensity of the SQW should be independent of the polarisation direction. In fact, the PL intensity of the SQW stays constant while the QWR

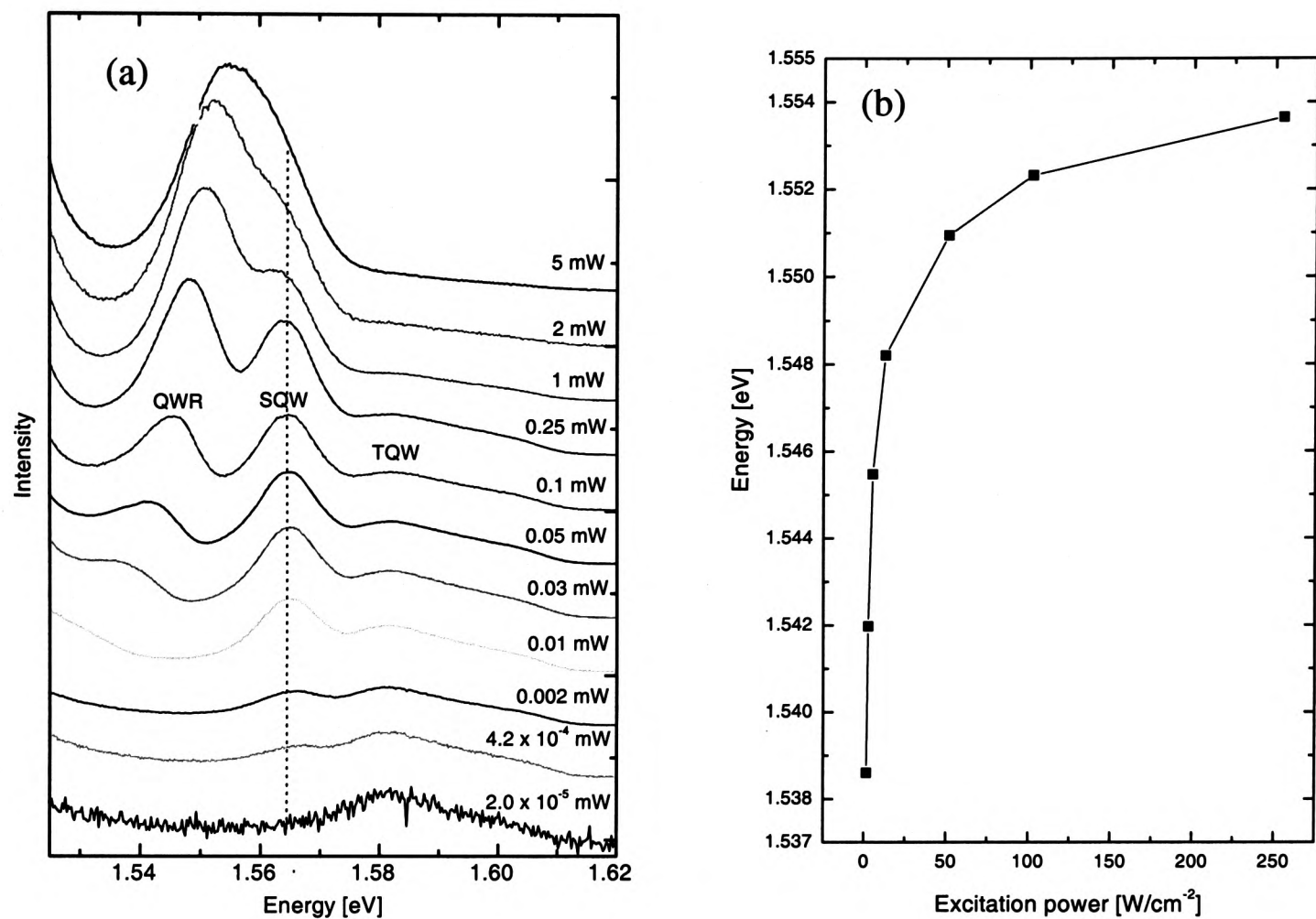


Figure 6.2: Photoluminescence spectra of sample D at varying excitation-power. A strong blue shift can be observed for the quantum wire-luminescence peak with increasing excitation power (a) . The shift is plotted-against excitation power in the semi-logarithmic graph (b).

peak has an anisotropy ratio $(I_{\perp}-I_{\parallel})/(I_{\perp}+I_{\parallel}) \sim -0.3$ which corresponds to the value calculated by Bockelmann et al. [1991] for free carrier absorption spectra in a $23 \text{ nm} \times 10 \text{ nm}$ QWR. Sample D is identical to C except that D was overgrown without the usual SiO_2 mask (cf. chapter 3.2) and has therefore a (100) top quantum well (TQW) between adjacent wires. The PL spectra in figure 6.2 a exhibit an additional peak from the TQW at around 1.59 eV. These measurements taken with an laser energy of 2.4 eV and varying power also reveal that the QWR peak position depends on the excitation power. At low intensities the wire PL lies at low energies and overlaps largely with the bulk GaAs peak. With increasing the power over

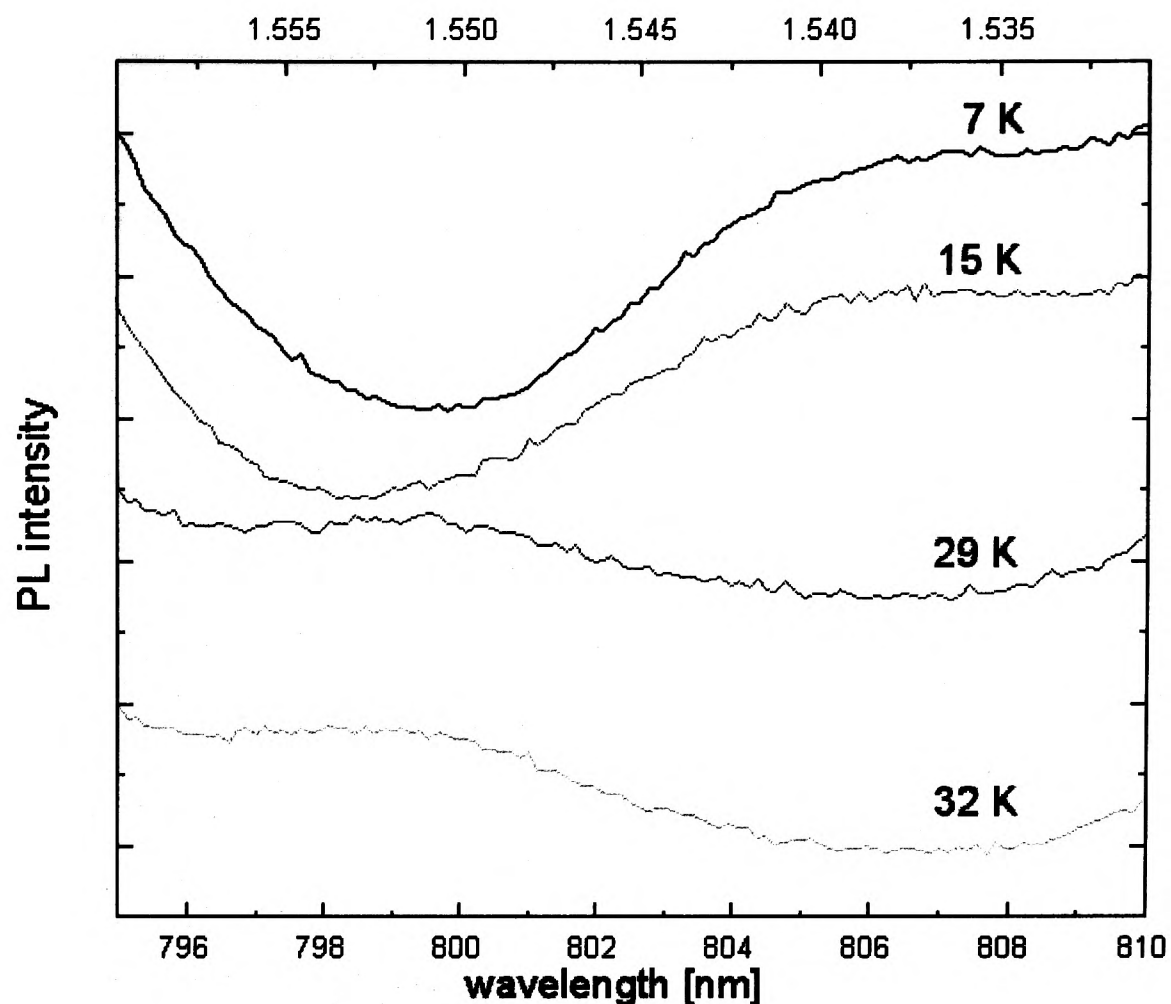


Figure 6.3: *Photoluminescence spectra of sample D at varying temperature.*

With increasing temperature and at a fixed excitation power the luminescence of the QWR increases in intensity at higher energies, which eventually (above 15 K) becomes stronger than the lower energy component, consistent with subband filling.

several orders of magnitude the QWR energy quickly blue-shifts and eventually pins 10 meV below the energy of the SQW peak, dominating the spectrum (fig. 6.2 b).

Increasing laser power is usually expected to increase the luminescence intensities of higher subbands due to state filling as it has been reported in undoped v-groove QWRs [Maciel 1994, Tribe 1997, Steer 1998]. This behaviour can not be observed in sample D, but on raising the sample temperature at fixed laser intensity an increase in intensity at higher energies (~ 10 meV) can be seen, which eventually becomes stronger than the lower energy component, consistent with filling of higher subband states.

The blue-shift of the wire luminescence could be explained by an optically-induced change of the self-consistent potential of the modulation-doped structure. The absorption of light creates an equal number of electrons and holes and does not change the local charge density. However, carrier relaxation within the structure can lead to separation of electrons and holes and consequently a change of the self-consistent potential.

It has been reported by Chaves et al. [1986] and others [Delalande 1986, Shields 1994], that in asymmetrically-doped quantum wells photoexcited electrons are “pulled out” of the undoped barrier region to the remote doped layer containing the ionised donors while the generated holes drift towards the 2DEG into the quantum well. There, the holes recombine with the electrons of the electron gas. The subsequently reduced 2DEG results in a reduction of the band bending and band renormalisation. For an electron concentration of n_s the blue shift of the PL peaks in a quantum well can be described as $-\Delta E_r = An_s + B\sqrt{n_s}$, where the linear term represents the effect of the band bending (cf. fig. 2.4) and the second term describes the effect of the band-gap renormalisation (BGR). However in v-groove QWRs BGR is expected to be small [Ambigapathy 1997] so that the dominating factor seems to be the reduction of the band-bending. It shifts both the electrons and the hole subbands levels to higher energies. The electrons being more sensitive than holes due to their lighter effective mass, the transition energy increases.

Both samples C and D show broad linewidths of 15 - 20 meV and the wire luminescence is energetically close to the GaAs and SQW luminescence, reflecting poor structural quality, doping non-uniformity and small confinement energies, respectively. This makes the experimental investigation of the optical properties difficult and therefore, quantum well thicknesses were decreased and the fabrication process systematically improved for the following samples.

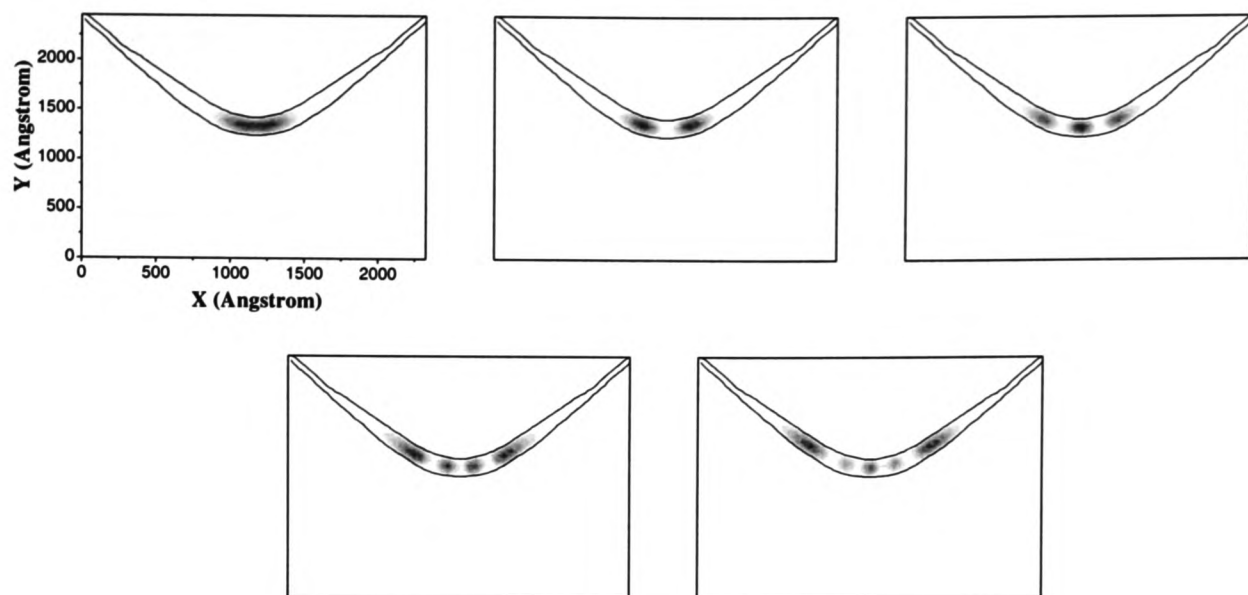


Figure 6.4: *Poisson-Schrödinger simulation for sample E.* The sample was grown using DMMAI as Al-source for the $\text{Al}_{30}\text{Ga}_{70}\text{As}$. The quantum wire is a wide crescent and therefore the electronic states are only weakly confined. The five states lie all within 15 meV.

(b) Sample E – The influence of alternative Al-sources

To examine the suitability of alternative Al-sources for the growth of v-groove QWRs samples were grown using DMMAI for the barrier material (cf. chapter 3.3). While for all other samples discussed in this thesis TMAI was used for the lower $\text{Al}_{30}\text{Ga}_{70}\text{As}$ layer. i.e. below the QWR, sample E was fabricated with a very similar growth programme as for sample C and D, but with DMMAI. As mentioned in chapter 3.3 the curvature at the bottom of such a wire is large and results in a smaller lateral confinement. This is accompanied by a wider crescent than observed in TMAI samples and no pinch-off region. The width of the crescent in sample E is around 200 nm, four times larger than in samples C and D.

Schrödinger-Poisson calculations (fig. 6.3) show that the electronic states are extended along the wide crescent and are only weakly confined. The first five states are found to be energetically close to each other, all lying within a range of 15 meV. As a result it is not possible to distinguish the QWR subbands from each other, but also the overlap with the

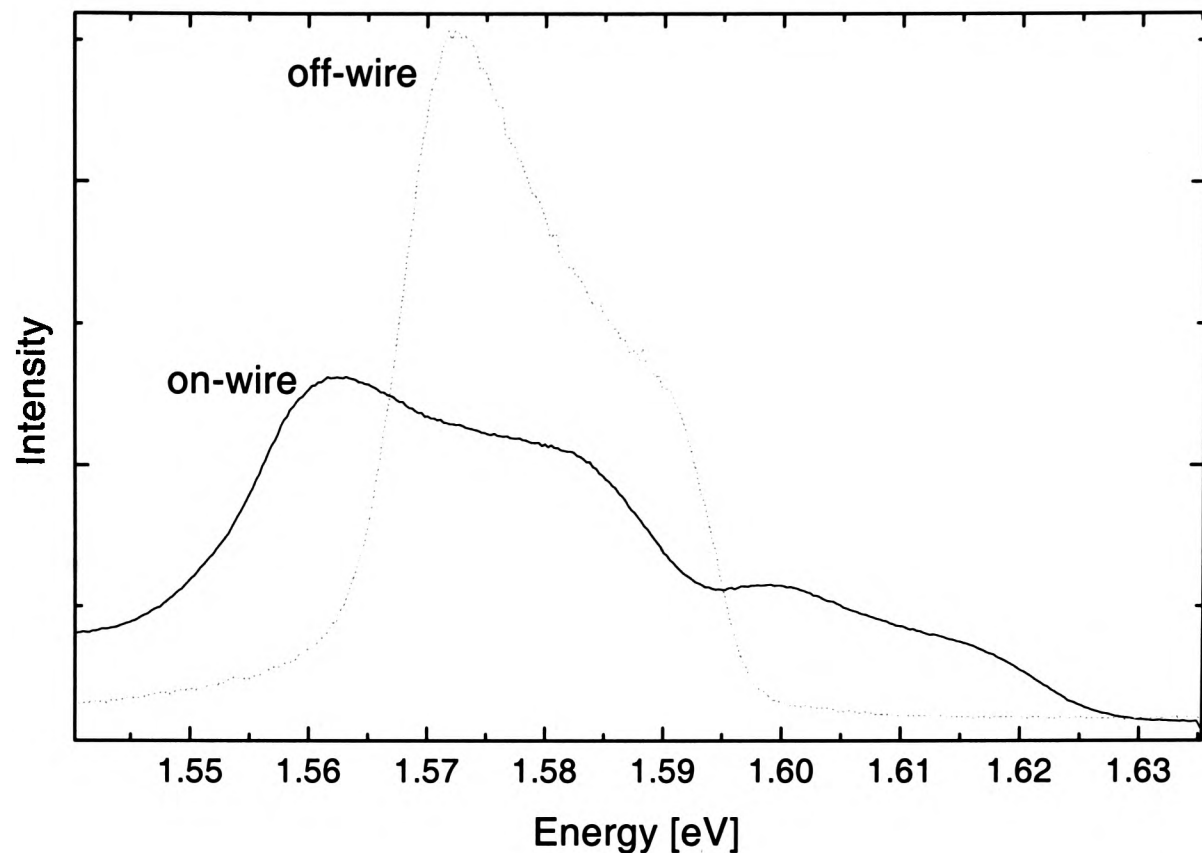


Figure 6.5: Photoluminescence spectra of the on-wire and off-wire region on sample E. The line of the off-wire luminescence exhibits the typical shape of a modulation-doped quantum-well. However, the PL of the on-wire region is poorly defined.

SQW luminescence is large, as seen in PL spectra (fig. 6.4). Judging from the off-wire spectrum, which shows the luminescence of a 10 nm quantum well, it could be speculated that the peak at 1.56 eV corresponds to the 18 nm thick QWR. As the off-wire quantum well peak resembles the typical lineshape of a modulation-doped quantum well, the shoulder at 1.58 eV in the on-wire spectrum could be interpreted as Fermi edge of the QWR. However, it cannot be excluded, that the shoulder originates from the SQW. In this case, the luminescence between 1.59 eV and 1.62 eV could be assigned to the TQW, as sample E was overgrown without a SiO-layer, like sample D. In subsequent samples a SiO₂-layer was always used to be able to exclude the luminescence from a TQW which unnecessarily complicates the optical spectrum.

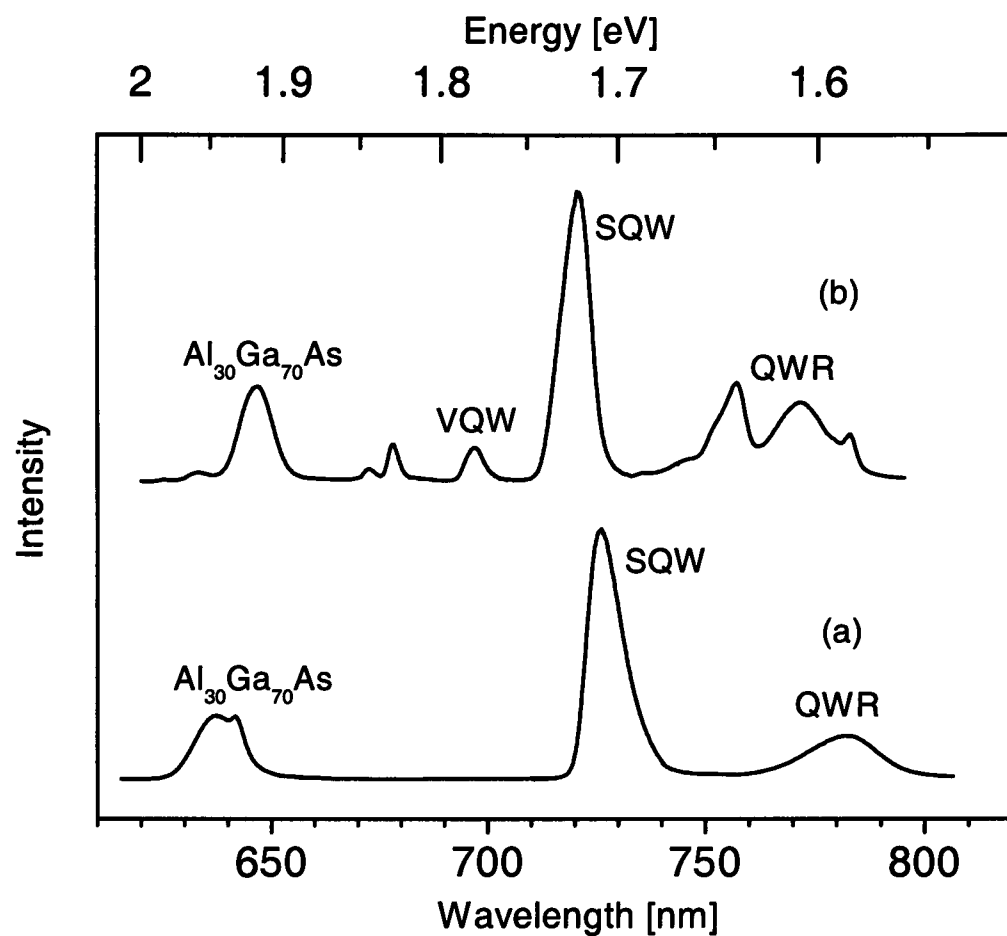


Figure 6.5: Photoluminescence spectrum of undoped sample A1 (a) and doped sample A2 (b). The spectrum from the doped sample shows additional peaks from the quantum wire (QWR) and the vertical quantum well (VQW)- while the side quantum well peak is slightly blue shifted.

The samples grown with DMMAI have shown only small lateral confinement compared to samples where TMAI was used. DMMAI was subsequently only chosen to initiate the polycrystalline growth on SiO₂ (cf. chapter 2.1) or for the upper barrier layer, i.e. above the GaAs quantum well layer.

(b) Sample A2

Sample A2 was fabricated with the same epitaxial growth programme as for undoped sample A1 (cf. chapter 5), except that A2 has two additional 10 nm modulation-doping layer with a Si-concentration of $n = 2 \times 10^{17} \text{ cm}^{-3}$ ($n = 1 \times 10^{17} \text{ cm}^{-3}$) in the upper (lower) dopant layer. As seen in PL experiments (fig. 6.5), the undoped sample A1 shows only single optical

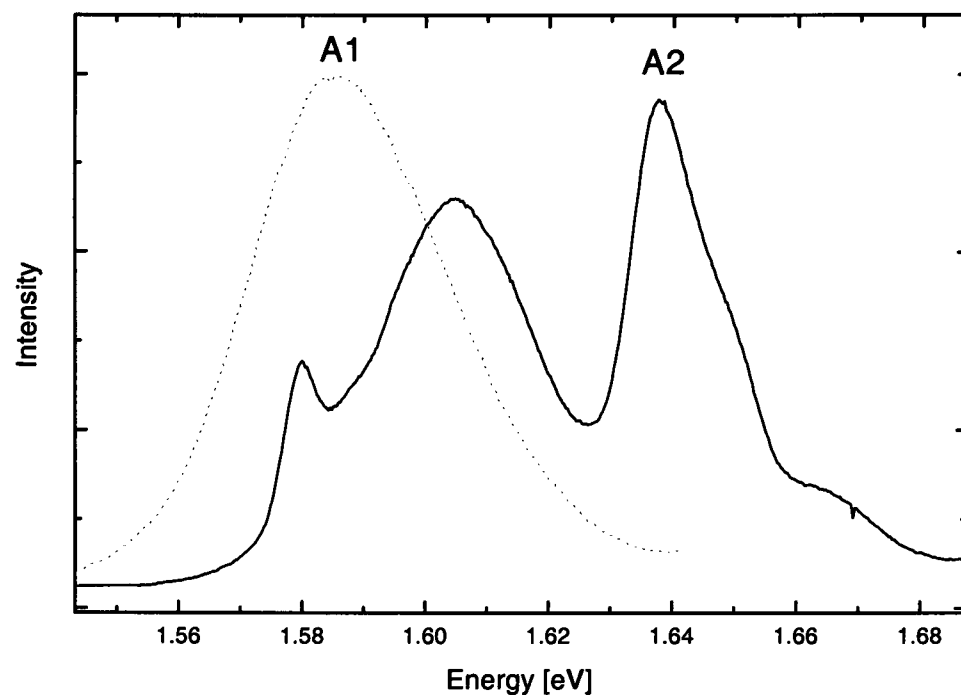


Figure 6.6: *Photoluminescence from the quantum wires in doped sample A2- and undoped sample A1.* While the spectrum for A1 is dominated by a single-broad peak, the PL from the doped sample exhibits three occupied subbands- and a high energy shoulder indicative of a Fermi edge.

transitions from each the QWR, the SQW, the bulk materials $\text{Al}_{30}\text{Ga}_{70}\text{As}$ and GaAs (latter not included in the spectrum). In contrast, sample A2 exhibits additional series of transitions, which arise from the modulation-doping.

In the region between the SQW and AlGaAs transitions the spectrum shows a peak at 1.790 eV which was assigned to the VQW and a group of three smaller peaks at around 1.835 eV. They could correspond to higher states of the VQW or QWR-like states in the upper corner of the SQW, as seen from cathodoluminescence pictures for sample B3 (see below fig. 6.10). Carriers photo-created in the VQW should relax rapidly into the QWR, and there should be little or no measurable recombination from the VQW [Kiener 1996b], which is true for the undoped sample A1. The doping, however seems to have an effect on the radiative recombination efficiency in the VQW. The positively charged donor ions which are also incorporated into the VQW could trap electrons, so they eventually recombine in the vertical structure.

Figure 6.6 shows the QWR luminescence from sample A2 in detail. The PL of undoped sample A1 appears in lighter grey for reference. While A1 features only one broad line,

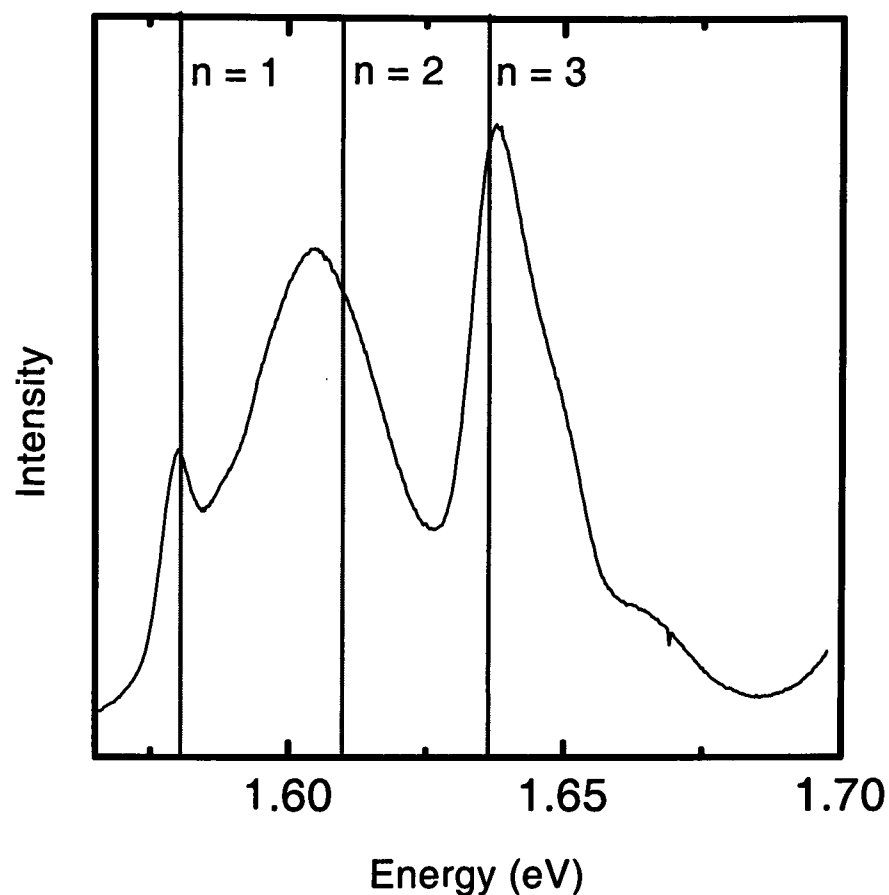


Figure 6.7: *Calculated quantum wire energy states for doped sample A2.-* The lowest three electronic states calculated with the Poisson-Schrödinger-solver match the three peaks in the photoluminescence spectrum identified as-optical recombinations from the quantum wire.

sample A2 consists of three peaks of different linewidths and a shoulder at the high energy side. By comparing with the undoped sample, but also due to the peak position relative to the SQW, it is evident that the luminescence from 1.56 - 1.68 eV has to originate from the QWR.

This is also confirmed by calculations with the Poisson-Schrödinger simulation as shown in figure 6.7. From the PL spectrum a linear charge density¹ of $\lambda = 3.5 \times 10^6 \text{ cm}^{-1}$ was derived and fed into the simulation together with the wire shape taken from TEM pictures. The result of the calculations yields three electronic states in the QWR, which energetically match the three peaks in the optical spectrum reasonably well. The shoulder at 1.668 eV is identified as the Fermi edge, as it can be seen in electro-PL measurements presented in chapter 8.4.

¹ The linear charge density can roughly be calculated, if the Fermi-energy and the DOS are taken into account.

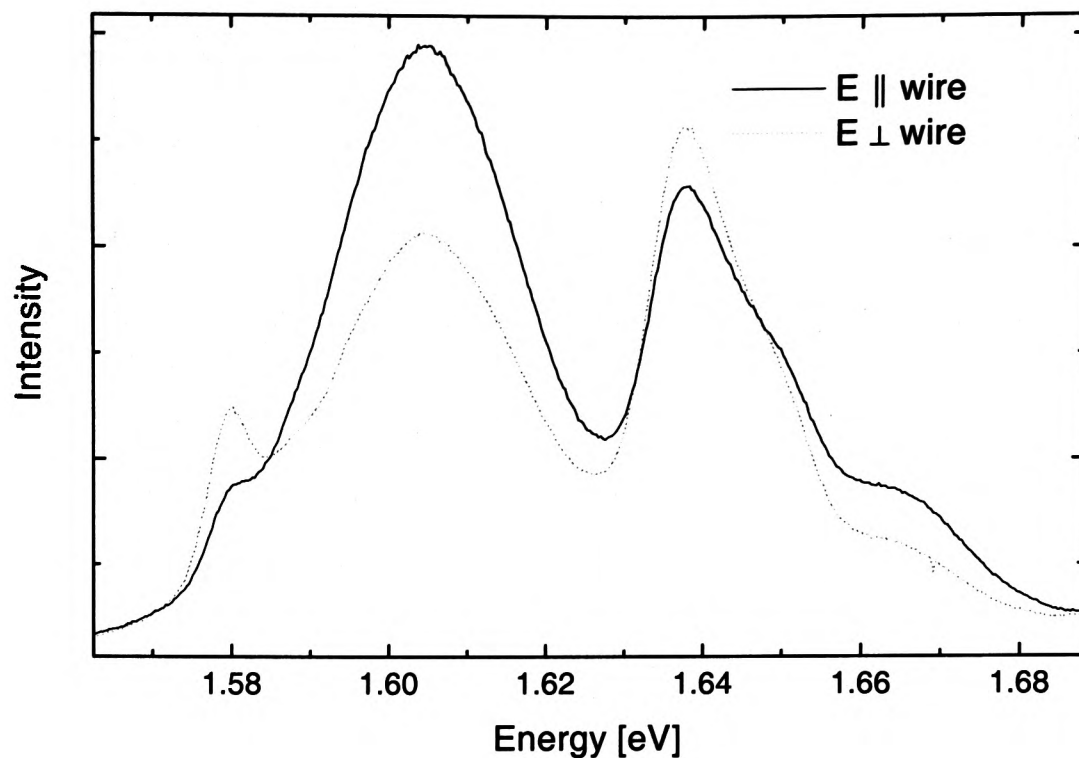


Figure 6.8: *Polarisation anisotropy of quantum wire luminescence.* Sample A2 shows alternating polarisation dependence of the electronic states due to valence band mixing.

It is not clear, what contributes to the different linewidths and intensities. Causes could include lateral wire size fluctuations within the wires and between the wires. With a SQW thickness of 2.85 nm and a QWR thickness of 7.6 nm, as measured in TEM pictures, even one monolayer fluctuation of around 0.3 nm will result in relative inhomogeneities. This again could lead to inhomogeneous broadening (~ 3 meV), and defects in the crystal structure could affect the rate of radiative recombination.

Figure 6.8 shows the polarisation dependent PL of sample A2. The peaks show strong and individually distinct differences in intensities for the polarised ($E \parallel \text{wire}$) and the depolarised spectra ($E \perp \text{wire}$). The PL from $n = 1$ is stronger in the depolarised arrangement. But, over the following peaks, the dependency alternates with every level. The mixing of the valence bands leads to polarisation anisotropies (cf. chapter 2), which – depending on the dominating hole character (heavy or light) of the mixed band – can result in relatively stronger polarised or depolarised PL. Therefore, the intensity dependencies reflect the hole character and with valence band calculations more quantitative statements could be made.

Concluding, sample A2 shows strong 2D confinement reflected in the polarisation anisotropy of the QWR luminescence and the large subband spacing. The doping of sample A2 has led to higher carrier concentration within structures particularly the QWR with three occupied subbands. Therefore A2 can be considered a successfully modulation-doped v-groove QWR. On the other hand, the linewidths of the PL peaks are still broad and too many occupied levels complicate the analysis of 1DEG properties. In the following, samples were grown with similar GaAs quantum well widths of around 3 nm, but with a further improved fabrication process and lower doping concentration or thinner dopant layers, respectively.

(d) Samples B2 and B3

Samples B2 and B3 are nominally identical to undoped sample B1, which has been described in chapter 5, except for the dopant layers. Sample B2 has a nominal doping of $n = 2 \times 10^{16} \text{ cm}^{-3}$ and $1 \times 10^{16} \text{ cm}^{-3}$ in the upper and lower doping layer respectively, which are each 10 nm thick. Sample B3 has a doping of $n = 1 \times 10^{17} \text{ cm}^{-3}$ in the upper and $5 \times 10^{16} \text{ cm}^{-3}$ in the lower modulation-doped layer and therefore is the strongest doped sample of the series.

Figure 6.9 shows the PL spectrum in the QWR region of all three samples B1 – B3. As discussed for B1 (cf. chapter 5), the sharp lines in the PL spectrum labelled $n = 1$ and 2 at 1.590 and 1.642 eV, respectively, are QWR states. However, one important difference to B1 is that in the PL of B2 as well as B3 the contribution from free carriers is expected to dominate over excitonic recombination due to the modulation-doping.

The luminescence which spans between the two peaks of the first two levels could originate from the polycrystalline material on top of the SiO_2 mask as it can be observed in the cathodoluminescence pictures (fig. 6.10) (cf. chapter 5.2). The high energy shoulder at 1.655 eV in the spectrum of B2 is indicative of the Fermi edge. Sample B3 exhibits a strongly pronounced peak at the same energy. Detailed investigations, which will be presented in chapter 7, determine this peak as a Fermi edge singularity (FES). One strong

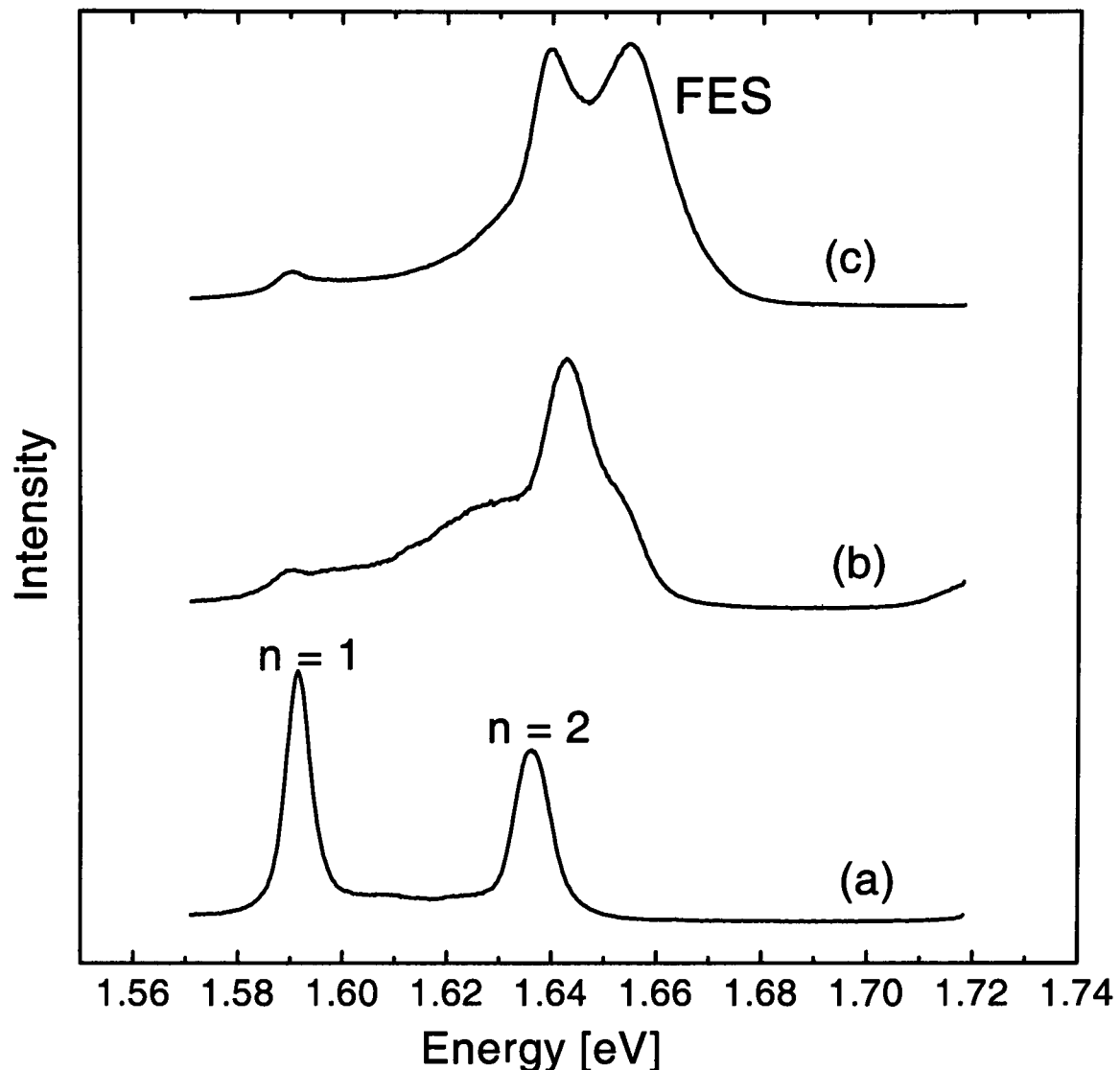
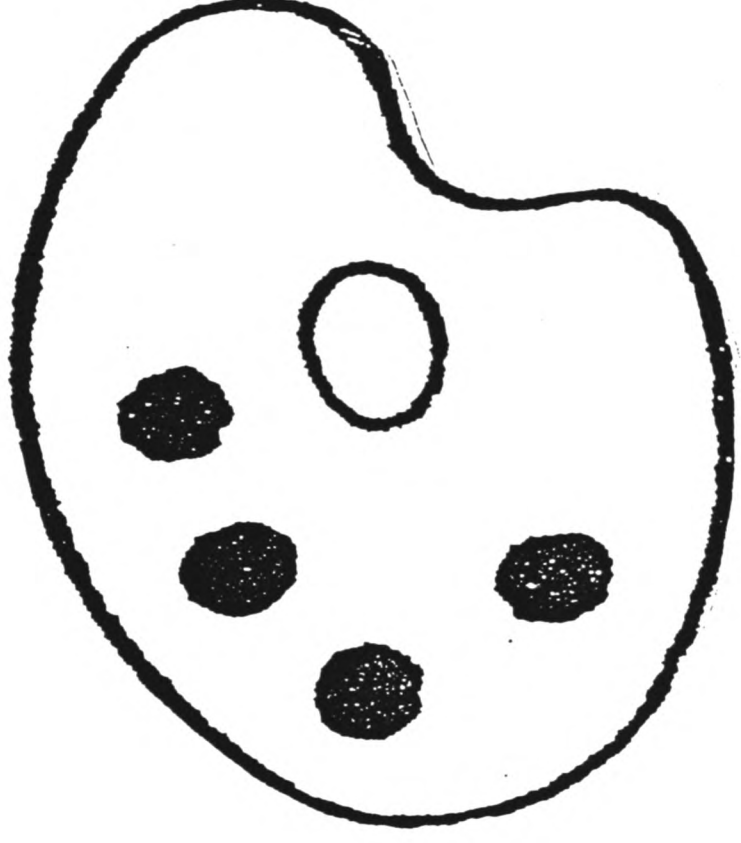


Figure 6.9: Photoluminescence spectra of samples (a) B1 (undoped) (b) B2 (doped) and (c) B3 (strongly doped). All samples from this set show transitions from the $n = 1$ and $n = 2$ subbands. However, the intensity of $n = 1$ is strongly reduced for the doped samples. They exhibit recombination from the Fermi edge and the peak from Sample A3 at this energy is indicative of a Fermi edge singularity (refer to chapter 7).

evidence for this interpretation is the very characteristic temperature dependence. As it will be shown, the singularity is quenched at a temperature of less than 20 K, which is expected theoretically. Other possibilities for the origin of this luminescence peak have been considered. The SQW has been determined to be much higher in energy, as explained for the undoped sample B1. An energy band calculation for a quantum well with a 3 nm quantum

ORIGINAL IN COLOUR



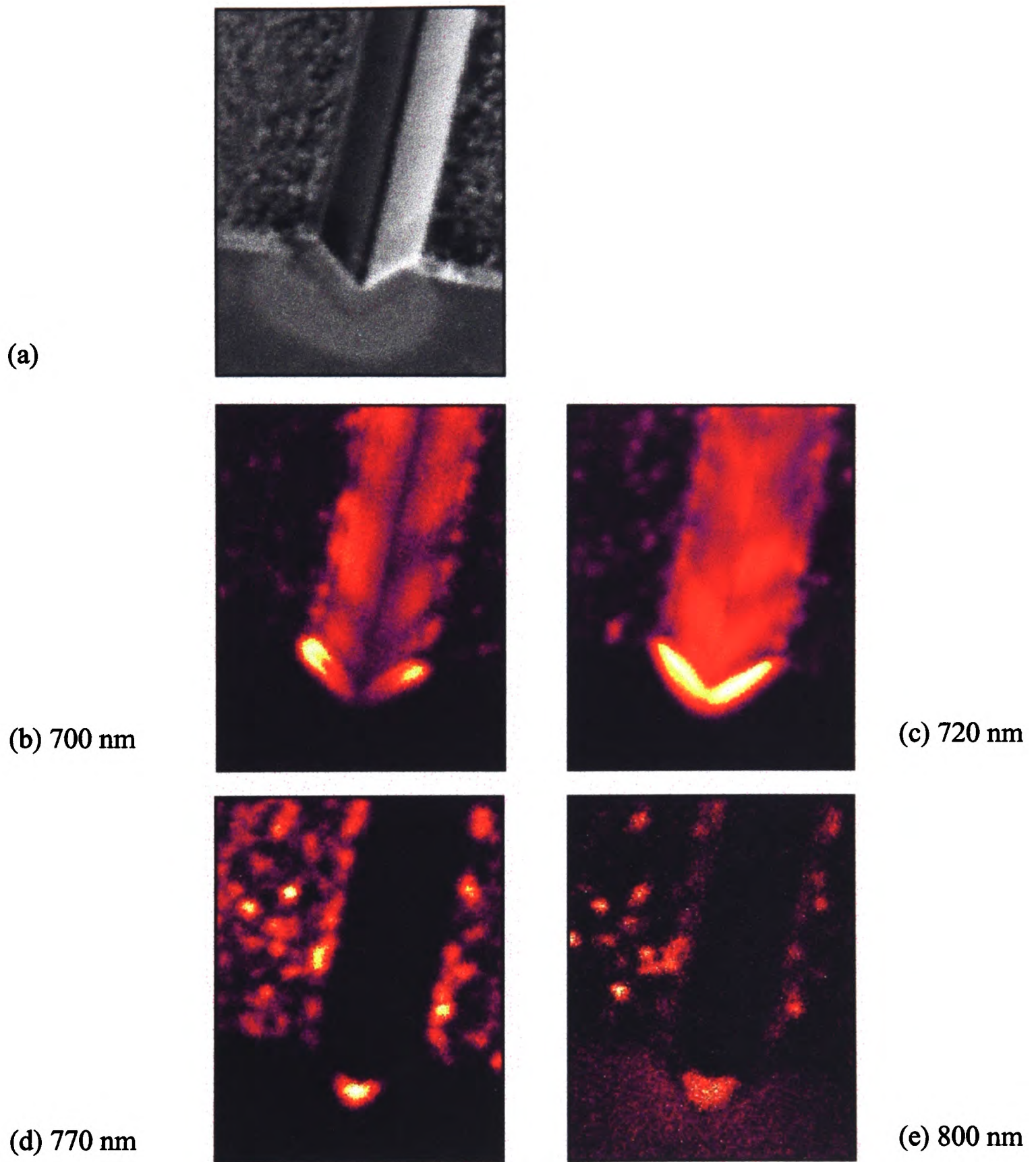


Figure 6.10: *Scanning electron microscopy (SEM) and cathodoluminescence (CL) pictures of highly doped sample B3. (a) shows an SEM picture. The following picture show the CL from different parts of the sample: (b) top corner of the side quantum well (c) side quantum well (d) and (e) quantum wire ($n = 2$ and 1).*

well yield a transition energy of 1.7 eV. All other potential candidates such as the VQW lie even higher in energy. It could also be reasoned that the FES in fact is the third wire level. However, the self-consistent procedure of the Poisson-Schrödinger calculation shows that the first three electronic states with a Fermi level, that would be consistent in the given context, would roughly be equidistant (cf. fig. 5.5). This is also expected due to the approximately parabolic lateral potential in v-groove QWRs (cf. chapter 2.5) That would mean, that the third peak would be 39 meV higher in energy than observed. This is also in agreement with PLE measurements presented in chapter 5.4. Furthermore, CL images do not show any other luminescence sources at around the energy of 1.65 eV, except from the QWR.

Two aspects of the optical spectrum, which have not yet been explained, are the relative intensities of the $n = 1$ and 2 peaks and that the levels do not shift to higher energies with increasing doping. The strong reduction of the $n = 1$ intensity on doping is unexpected for a simple non-interacting 1DES. The experimental lack of band-edge singularities can be attributed partially to disorder broadening, but similar to the discussion in chapter 5.5, it probably is mainly a consequence of intrinsic Coulomb correlation effects resulting in a vanishing oscillator strength for the band-edge transition.

In quantum wells a shift of transition energies to higher energies is expected with increasing doping. However, various considerations could explain the rigidity of the energy levels seen in sample B2 and B3. An explanation could involve many-body effects such as band-gap renormalization [Cingolani 1993] which would lower the conduction band energies, although it has been found to be very small in v-groove QWRs [Ambigapathy 1997] (cf. chapter 5.5). Another possibility is the pinning of the wire levels by surface states. Whether one of these processes or a combination of them dominate will have to be determined in further investigations.

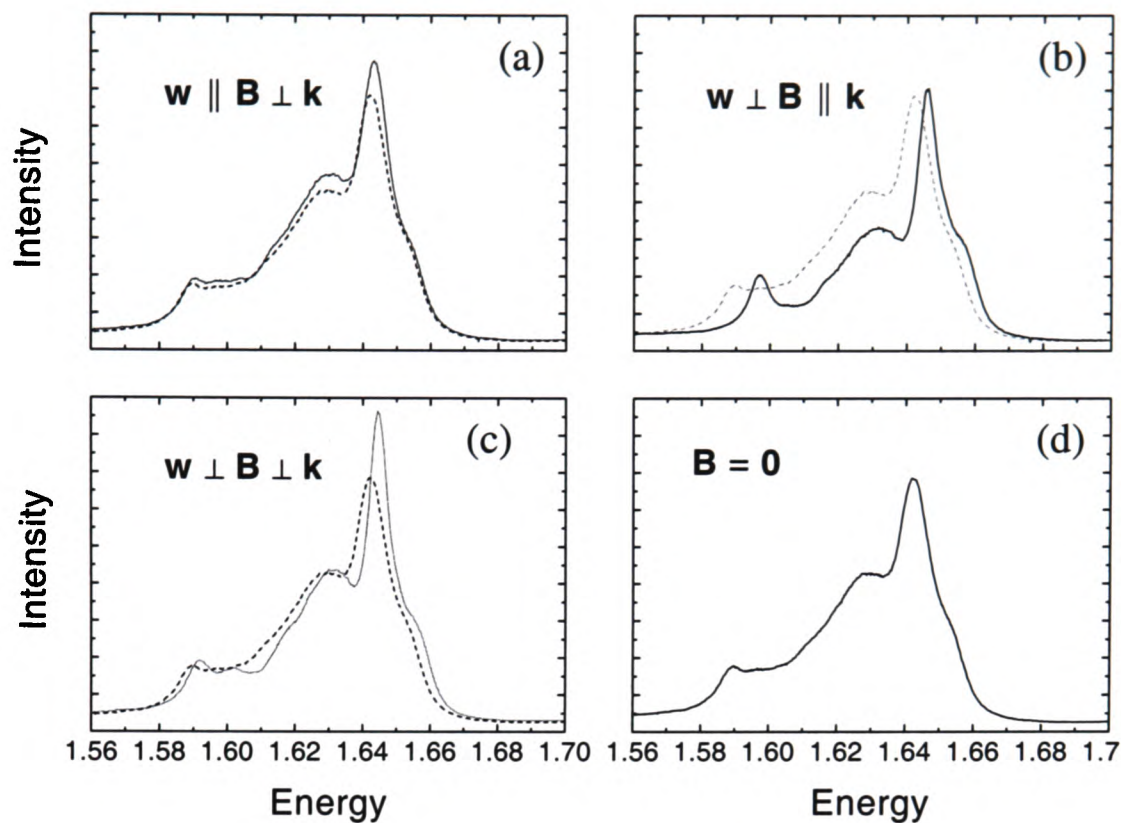


Figure 6.11: *Magneto-photoluminescence of sample B2 at $B = 15.5$ T in three configurations and at $B = 0$ T. Due to the anisotropic 2D confinement in the quantum wire, the shifts of the PL peaks are different for each direction. The strongest shift is observed of the weakest confinement and vice versa.*

6.3 MAGNETO-OPTICAL EXPERIMENTS ON DOPED SAMPLES

Magneto-PL (MPL) experiments were performed on the doped samples B2 and B3 identical to the ones done on undoped sample B1 (cf. chapter 5.4). An argon laser was used as excitation source using the 2.4 eV transition and the samples were cooled in a cryostat at 1.4 K. The magnetic field up to 14 T was produced by a superconducting magnet. As before, the different experimental configurations will be described in terms of the wire direction w , the direction of the magnetic field vector B and the wavenumber vector k of the PL spectra which is parallel to the growth direction.

(a) Sample B2 – 1DEG in an applied magnetic field

In figure 6.11 the optical spectra of sample B2 for (d) $B = 0$ and $B = 15$ T for the configurations (a) $w \parallel B \perp k$, (b) $w \perp B \parallel k$ and (c) $w \perp B \perp k$ are shown. The dotted graphs

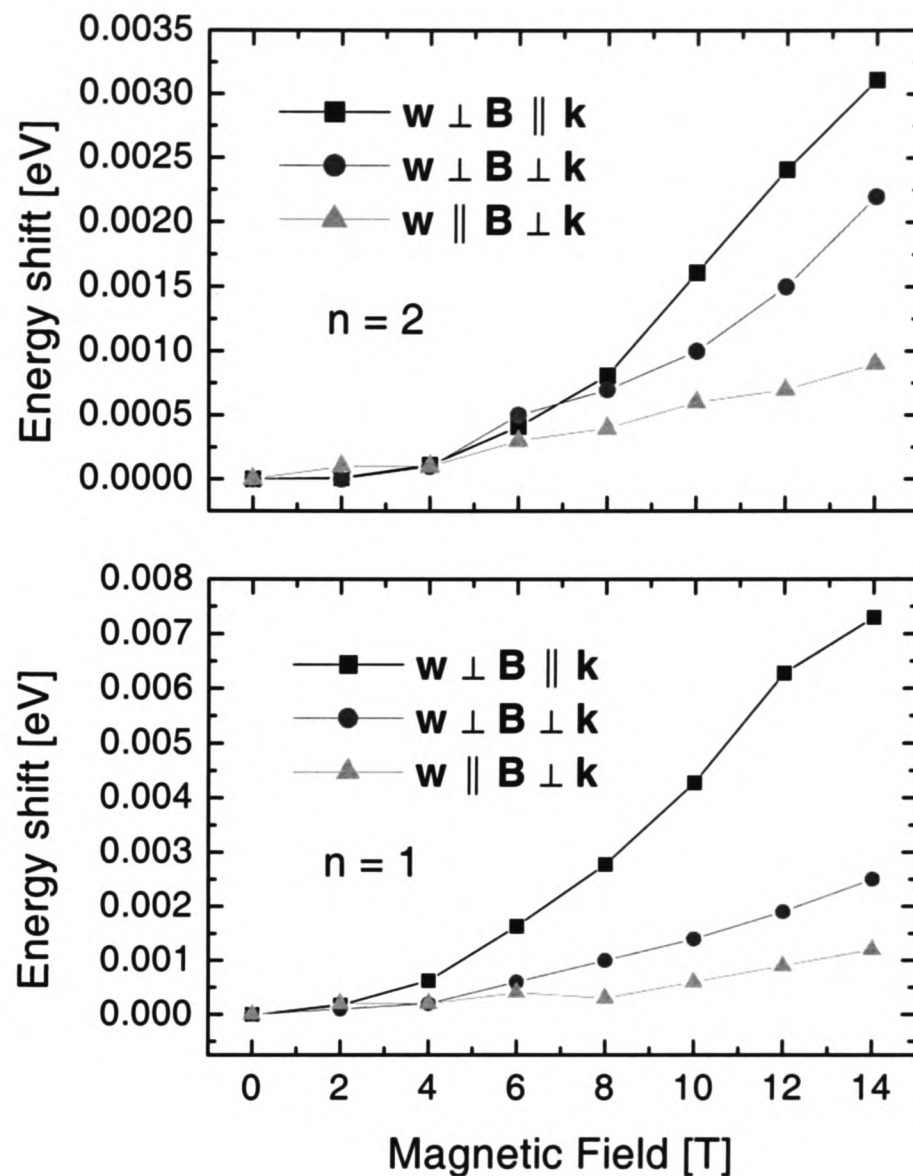


Figure 6.12: Energy shifts of $n = 1$ and 2 peak positions plotted against applied magnetic field. The figures for both levels exhibit the expected shift anisotropy. The shifts are stronger for $n = 1$ than for $n = 2$, as the second electronic state is squeezed into the narrower corners of the quantum wire crescent.

repeat the $B = 0$ spectrum for comparison. As observed for undoped sample B1 the luminescence energies shift when a magnetic field of 15 T is applied. For the $w \perp B \parallel k$ configuration this effect is the strongest and on the other hand is the weakest for the case where the B-field is parallel to the wire. This is clearly seen in figure 6.12, where the shifts are plotted against the magnetic field for both electron levels and all three field directions. The energy shift anisotropy reflects the 2D confinement, and the strongest shift is observed

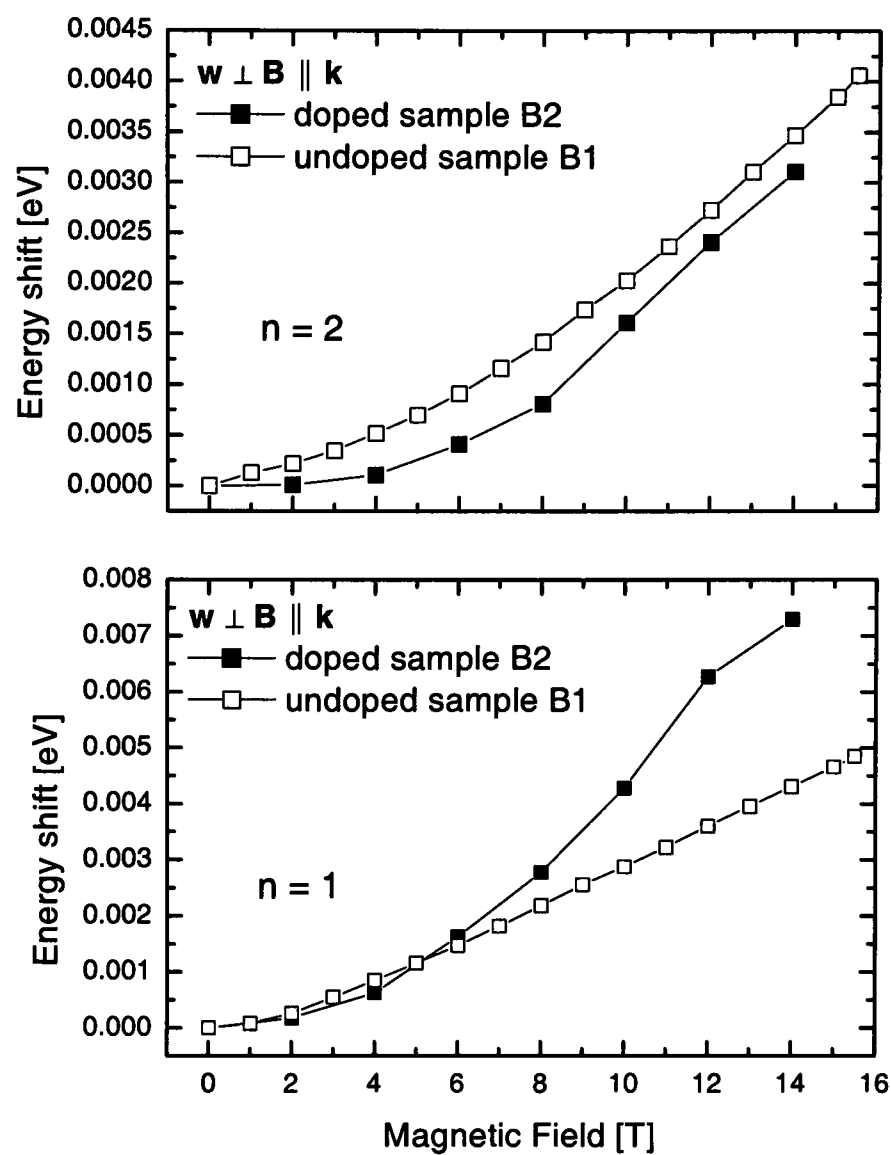


Figure 6.13: Comparison of energy shifts of luminescence peaks in magnetic fields in doped (B2) and undoped samples (B1) for $n = 1$ and 2 . The $n = 1$ shift is stronger in doped samples, whereas the $n = 2$ shift is stronger in undoped samples. This is due to the fact, that the first state is spatially wider in doped samples, while the second one is squeezed stronger into the quantum wire corners.

where the confinement is the smallest and vice versa. Qualitatively, these results are consistent with the ones obtained for the undoped sample B1 (cf. chapter 5.4).

In direct comparison, however, the influence of the doping can be recognised. In figure 6.13 the energy shift of samples B1 and B2 are plotted for the $w \perp B \parallel k$ direction. The shifts of

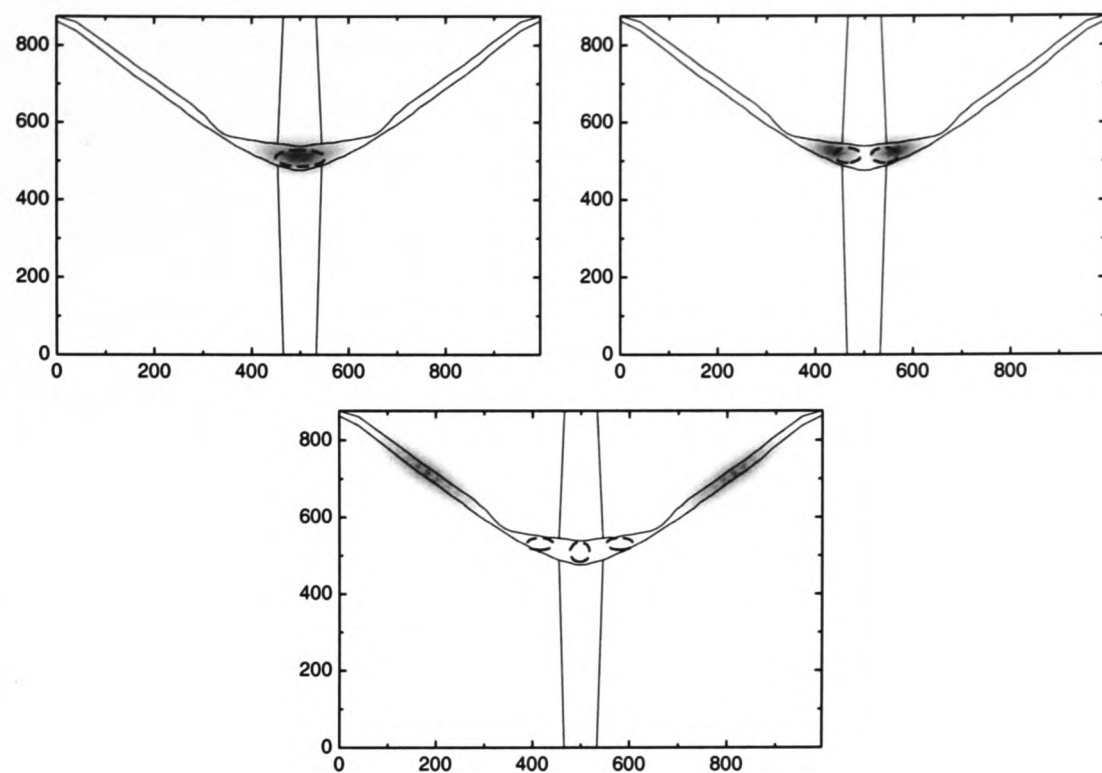


Figure 6.14: *Calculated charge density distributions for the three lowest electron states in highly doped sample B3. While the first two states reside within the 1D region, the linear charge density of $\lambda = 1.5 \times 10^8 \text{ m}^{-1}$, used for this simulation, is high enough to squeeze the third state into the side quantum well (undoped case also shown as broken line ellipses).*

the $n = 1$ peaks for both samples are comparable at low field. But as expected for free carrier recombination, the parabolic shift of sample B2 soon recovers the linear Landau shift and moves to higher energies stronger than the exciton luminescence peak of sample B1. The magnetic field at which the transitions occurs is given by the cyclotron diameter which equals the wire width. Rinaldi et al. [1994a, b] estimate fields of 4 to 5 T for a 10 nm thick and about 40 nm wide v-groove QWR, which correspond to the dimensions of the samples B1-B3.

The $n = 2$ peak of the doped sample on the other hand, exhibits a slower blue shift than the equivalent peak of the undoped sample. This can be understood when the spatial extent of the electronic states is analysed. The solution of the Poisson-Schrödinger solver for sample B2 is shown in figure 6.14. The first two states can be found in the QWR, whereas the third

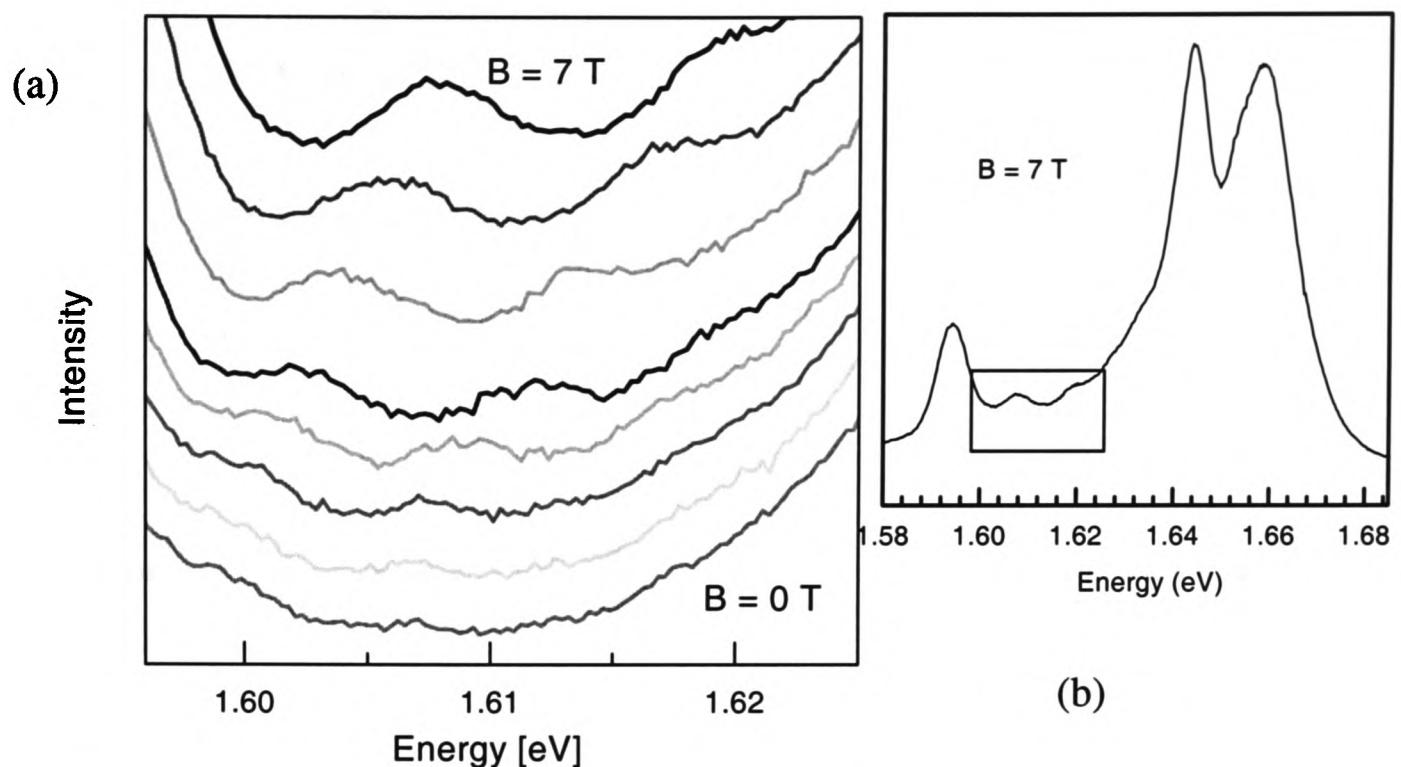


Figure 6.15: Observation of substructure in the magneto-photoluminescence of sample B3 between $n = 1$ and 2 (b). Figure (a) shows fine structure between $n = 1$ and 2 which is consistent with hole states: this recombination is weakly allowed at $B = 0$ due to the complex shape of the confining potential. The magnetic field was increased from 0 – 7 T in 1 T steps.

level is pushed into the SQW due to the repulsive potential of the high electron density in the QWR. Relating these states to the ones obtained for the undoped sample (cf. fig. 5.4), a change in the wavefunction distribution can be observed due to the doping. The first state is wider and squeezes the second state further towards the narrow lateral corners of the QWR. As a consequence, the $n = 2$ state has become more confined and therefore requires higher magnetic fields to decrease the cyclotron diameter to the dimension of the $n = 2$ state. This would explain the small shift at low magnetic fields and the late transition from parabolic to linear shift at around 8 T.

(b) Sample B3 – Valence band structure

The spectrum on the right in figure 6.15 (b) shows the PL spectrum of B3, while a magnetic field of $B = 7$ T is applied perpendicular to the surface of the sample. In figure 6.15 (a)

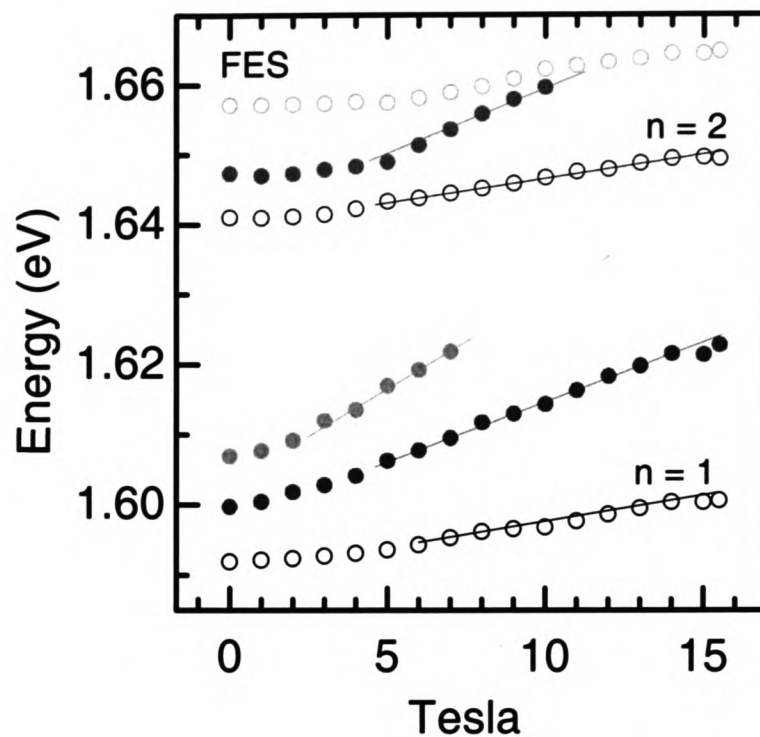


Figure 6.16: *Fan diagram showing the B -dependence of the 1D states. The shift of the fine structure (solid circles) from figure 6.15 exhibits cross-over to Landau quantization for $B > 5$ T. Also shown are the $n = 1$ and 2 as well as the Fermi edge singularity (FES) peak positions.*

additional fine structure occurring in the spectral region between the $n = 1$ and $n = 2$ lines is shown in detail. At low fields the features are very weak, and shift only slightly with increasing field. However, for $B > 5$ T we see that they begin to shift more rapidly to higher energy.

The fan diagram in fig. 6.16 summarizes the results. It is quite clear that at high fields these lines form a Landau series: i.e. there is a cross-over from one-dimensional confinement to Landau quantization as the cyclotron energy becomes comparable to the confinement energy. However, the energy scale at $B = 0$ in this series is clearly not electronic in origin, but in fact is consistent with valence band states. A definitive assignment of the lines will require a detailed calculation of the valence band energy levels and effective masses; however, using accepted values of m_e and m_h for GaAs, the weak PL features at zero field are consistent with $n_e = 1$, $n_h = 1, 3, 5 \dots$ electron-hole transitions which are weakly allowed

due to the complex shape of the confining potential. At intermediate fields the confined hole states transform into Landau states $l_h = 0, 2, 4$. The heavy-light character of the hole states concerned is quite complex since there is already strong mixing at $k = 0$ and $B = 0$.

6.4 MAGNETO-TRANSPORT

Apart from optical methods of measuring the influence of modulation-doping on the samples, they were also investigated electrically. For this purpose, specifically designed structures were developed, where single wires of defined length and width are provided with ohmic contacts at both ends (fig. 3.2). These sample were then used for magneto-transport measurements.

This method delivers a series of useful information about the QWRs, as carrier concentration and an upper estimate for the mobility. But more importantly, evidence for one-dimensional properties are expected in the characteristics of the electrical spectra, namely weak localisation at $B \approx 0$ and Shubnikov-de Haas (SdH) oscillations periodic in $1/B$.

The electron density n_e can be calculated from the oscillations with

$$n_e = \frac{2e}{h} \left(\frac{1}{B_1} - \frac{1}{B_2} \right)^{-1} \cos(\theta - \varphi), \quad (8.6)$$

where B_1 and B_2 are the magnetic fields corresponding to two successive oscillation maxima in r . θ is the $\mathbf{B}$ -field orientation and φ the angle of the conductive layer with respect to the sample (100) surface.

The one-dimensional weak localisation is a quantum mechanical effect which is characteristic for one-dimensional transport. The so-called classical return probability $C(t)d\mathbf{r}$ describes the likelihood of an electron returning to an environment $d\mathbf{r}$ within the time t . While the time dependence of $C(t)$ for electrons in two dimensions is $1/t$ in one dimension it is $1/\sqrt{t}$. The latter leads to an increase of the specific resistance at low temperatures.

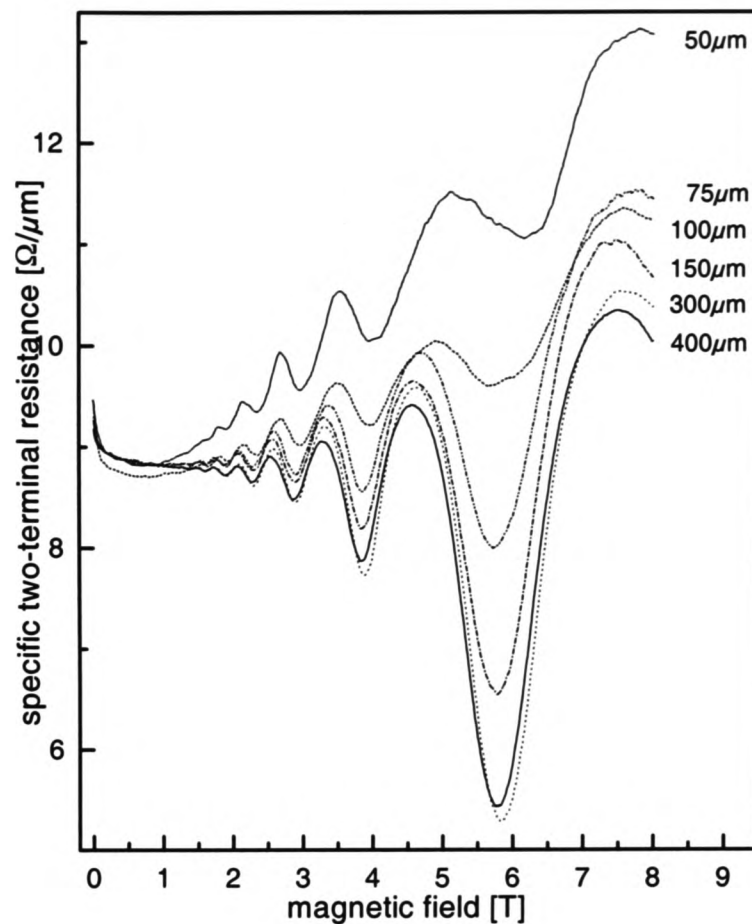


Figure 6.17: Magneto-transport measurements for different wire-lengths of single wire samples, measured in a two terminal configuration at 1.4 K with an ac current of 10 nA. The curves represent resistances per μm wire length.

Figure 6.17 shows the magneto-resistance measurement of QWRs with a 7 nm GaAs well and a modulation-doping of 4×10^{17} and $2 \times 10^{17} \text{ cm}^{-3}$ in the upper and the lower barrier layer, respectively². The groove width for all wires is $2 \mu\text{m}$, while the lengths vary from 50 to $400 \mu\text{m}$. The samples were measured in a two terminal configuration at a temperature of 1.4 K and using standard lock-in techniques with an ac-current of 10 nA.

² The sample was grown with a similar layer sequence as sample C.

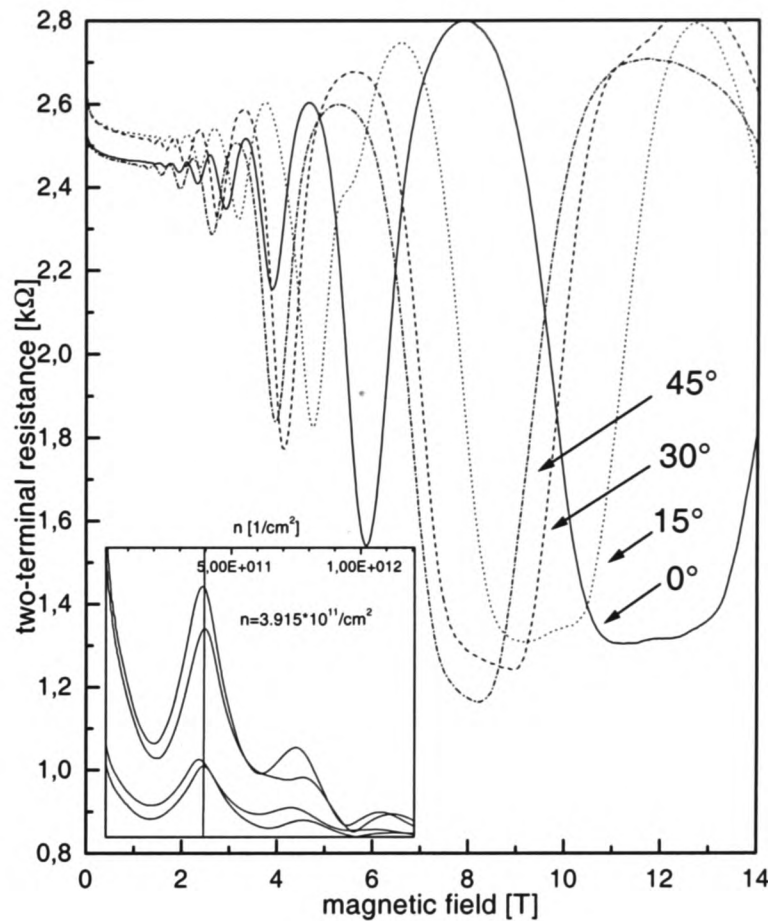


Figure 6.18: Transport measurement of a 300 nm wire structure for different tilt angles of the magnetic field. Inset shows Fourier transform for 45°.

At weak magnetic fields the weak localisation is suppressed and a contact resistance can be extrapolated from the resistances of the wires with different lengths l . For $l \rightarrow 0$ the contact resistance can be determined as $R_c = (150 \pm 15) \Omega$. The specific resistance for the wires yields $\rho_v = r(l)/l = (8.94 \pm 0.1) \Omega/\mu\text{m}$.

To identify, whether the SdH oscillations originate from the SQW or the QWR the sample was tilted with respect to the magnetic field (fig. 6.18). These angle dependent measurements do not rule out the possibility that most of the transport occurs through the SQW. In this case the carrier concentration can be determined for all θ as $n_e = 3.9 \times 10^{11} \text{ cm}^{-2}$.

This concentration is much higher than in two-dimensional systems with similar doping concentrations grown on (100) surfaces. However, doping on (111)A substrates generally is not more efficient, but differs on pre-patterned surfaces with partly polycrystalline growth.

Judging from the magneto-transport measurements to date, it is difficult to identify evidence for one-dimensional transport. The doping levels are too high, so that states in the SQW are occupied, where the conduction dominates. To avoid an occupancy of these states, either the doping level would have to be lowered or a gate on top of the structure would have to be used, in order to deplete the higher levels.

However, if the transport in the QWR is neglected, an upper limit for the classical mobility $\mu = 600.000 \text{ cm}^2(\text{Vs})^{-1}$ for the SQW can be obtained from the angle-dependent measurements.

6.5 CONCLUSIONS AND OUTLOOK

The results of this chapter have demonstrated the successful fabrication of modulation-doped v-groove QWRs. The improvement of the fabrication and the development of a high quality sample with large subband spacings was made possible through a systematic investigation of optical properties. The investigation of these doped structures have lead to the following findings:

- The development of high quality samples required the variation of several fabrication parameters as quantum well layer thickness, various fabrication related values, Al-source and SiO₂-masking. The best results were obtained for samples with $\leq 3 \text{ nm}$ quantum well layer thickness, TMAI as Al-source, a SiO₂-mask to avoid a formation of a TQW and relatively low doping.
- One of the next major goals in terms of fabrication would be to produce a QWR in the extreme quantum limit, i.e. a degenerate 1DEG in one occupied subband with large subband spacings.

- Increasing excitation power leads to a blue-shift of the QWR luminescence peak in sample D due to band-bending. The photogenerated electrons are separated from the holes due to the positively charged donor ions. The holes move into the QWR and lead to a reduction of the 1DEG and subsequently to a reduction of band-bending.
- The samples from the B series (B1 - B3) exhibit linewidths as narrow as 6 meV and almost 50 meV subband separation. An effect of the doping can be clearly seen in PL spectra of sample B2 and B3.
- A FES is observed in sample B3, demonstrating the formation of a degenerate 1DEG. The FES will be elaborated on in the following chapter 7.
- The reduction of the $n = 1$ PL peak in doped samples B2 and B3 could be caused by the random potential arising from ionised donors in the barrier. The origins of this need to be investigated further.
- As seen in undoped sample, an anisotropy of the energy shifts of the QWR peaks in applied magnetic fields could be observed for doped samples, demonstrating the 2D confinement.
- The direct comparison of the magneto-PL measurements from the undoped with the ones of the doped reveals the change of spatial extent of the electronic states; the first state is wider in the doped sample squeezing the second state further into the corners of the QWR. This is also confirmed by calculations with the Poisson-Schrödinger solver.
- Moreover, a fine structure occurs with increasing magnetic field between the $n = 1$ and 2 PL peaks. The energies of the additional peaks are consistent with hole energies. At high fields the lines plotted in a fan diagram form a Landau series.
- From magneto-transport experiments no clear indication for one-dimensional transport can be found. Angle-dependent spectra support the assumption that the Shubnikov-de Haas oscillations originate from the SQW. In further research samples

with less doping need to be examined, so that a transfer of electrons from the QWR into the SQW can be excluded.

- However, a carrier concentration of $n_e = 3.9 \times 10^{11} \text{ cm}^{-2}$ and mobility of $\mu = 600.000 \text{ cm}^2(\text{Vs})^{-1}$ can be identified from the electrical measurements.

CHAPTER 7

FERMI EDGE SINGULARITIES

CONTENTS

7.1	INTRODUCTION	116
7.2	BASIC THEORY OF FERMI EDGE SINGULARITIES ..	117
7.3	FERMI EDGE SINGULARITIES IN PHOTOLUMINESCENCE SPECTRA.....	120
7.4	TEMPERATURE DEPENDENCE	120
7.5	FERMI EDGE SINGULARITY IN A MAGNETIC FIELD	123
7.6	DISCUSSION	125
7.7	CONCLUSIONS AND OUTLOOK.....	129

7.1 INTRODUCTION

Modulation-doped QWRs are ideal for studying many-body properties as the one-dimensional electron gas (1DEG) interacts only weakly with scattering centres; the 2D confinement provides a reduced phase space and the method of modulation-doping separates the carriers from the dopant impurities. This reduced scattering rate manifests for example in high electron mobilities predicted by Sakaki [1980, see also Motohisa 1992] and observed experimentally for instance by Ando [1982]. Many body singularities in quantum wells and wires have attracted a lot of theoretical interest [Mahan 1990, Müller 1992, Rodriguez 1993, 1994] and have been investigated experimentally in etched quantum well structures [Calleja 1991, Chen 1990, Fritze 1993].

In this chapter the observation of strong Fermi edge singularities (FES) in the photoluminescence spectrum of modulation-doped v-groove QWRs is reported. FES are predicted to appear in the optical spectrum of a degenerate 1DEGs due to a collective response of the electrons to the Coulomb potential of a photoexcited valence band hole: in a 1DEG this singularity is expected to be strongly enhanced due to restrictions imposed on hole recoil [Hawrylak 1992, Rodriguez 1993].

The behaviour of the singularity has been investigated under lattice and electrical heating. Creating hot electrons produces a strong reduction of the singularity due to Fermi surface smearing. Applying high photoexcitation also increases the electron temperature, but on the other hand it generates a high-density of electrons and holes which partly compensates a reduction of the FES. Finally, the influence of a static magnetic field on a FES has been investigated. The enhancement of the FES by subband mixing is consistent with theoretical predictions.

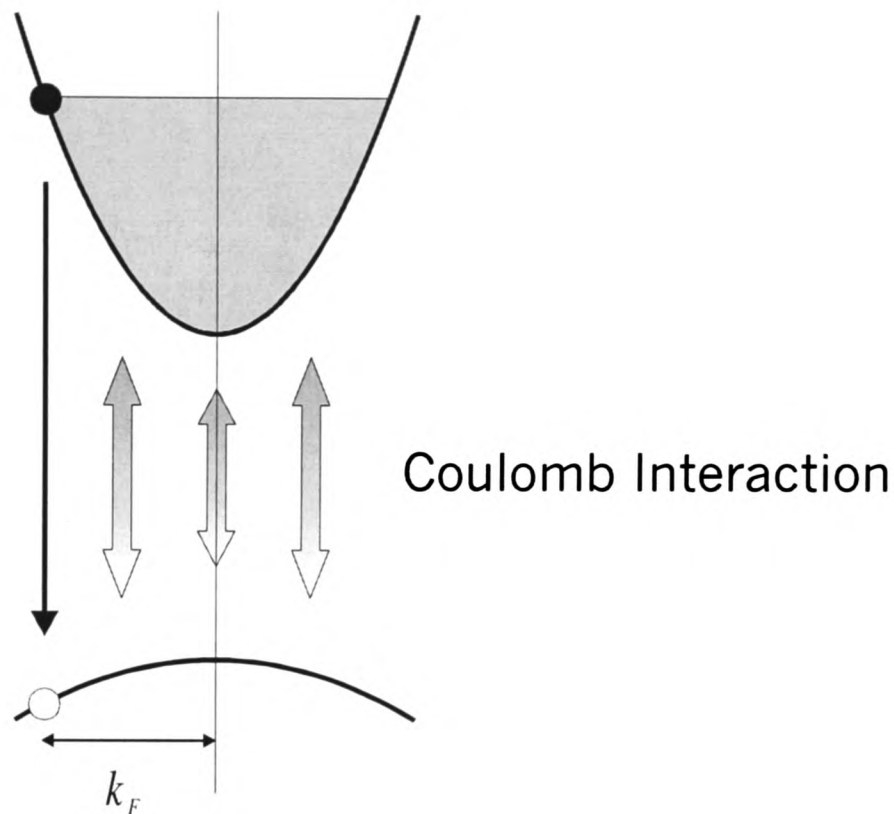


Figure 7.1: *Two band model for describing the occurrence of Fermi edge singularities.* In a degenerate 1D system an electron-hole pair is created by photoexcitation. The $N + 1$ electrons in the conduction band respond collectively to the sudden switching on of the hole potential. A subsequent recombination occurs preferentially with electrons from the Fermi edge leading to an enhancement of optical transitions from the Fermi energy.

7.2 BASIC THEORY OF FERMI EDGE SINGULARITIES

The FES was originally proposed by Mahan for soft x-ray absorption in metals [Mahan . 1967] and was later refined by Nozieres and De Dominicis (the MND problem) [Nozieres 1969]. A review on the MND problem can be found in Mahan [1990] or Ohtaka [1990]. Here, the occurrence of FES in the electron gas of a strongly-confined, modulation-doped QWR will be outlined. For simplification the model used comprises only one valence band and one conduction band in which the subband spacing is larger than the Fermi energy E_F , i.e. a 1D system in the so called extreme quantum limit (fig. 7.1). The model will

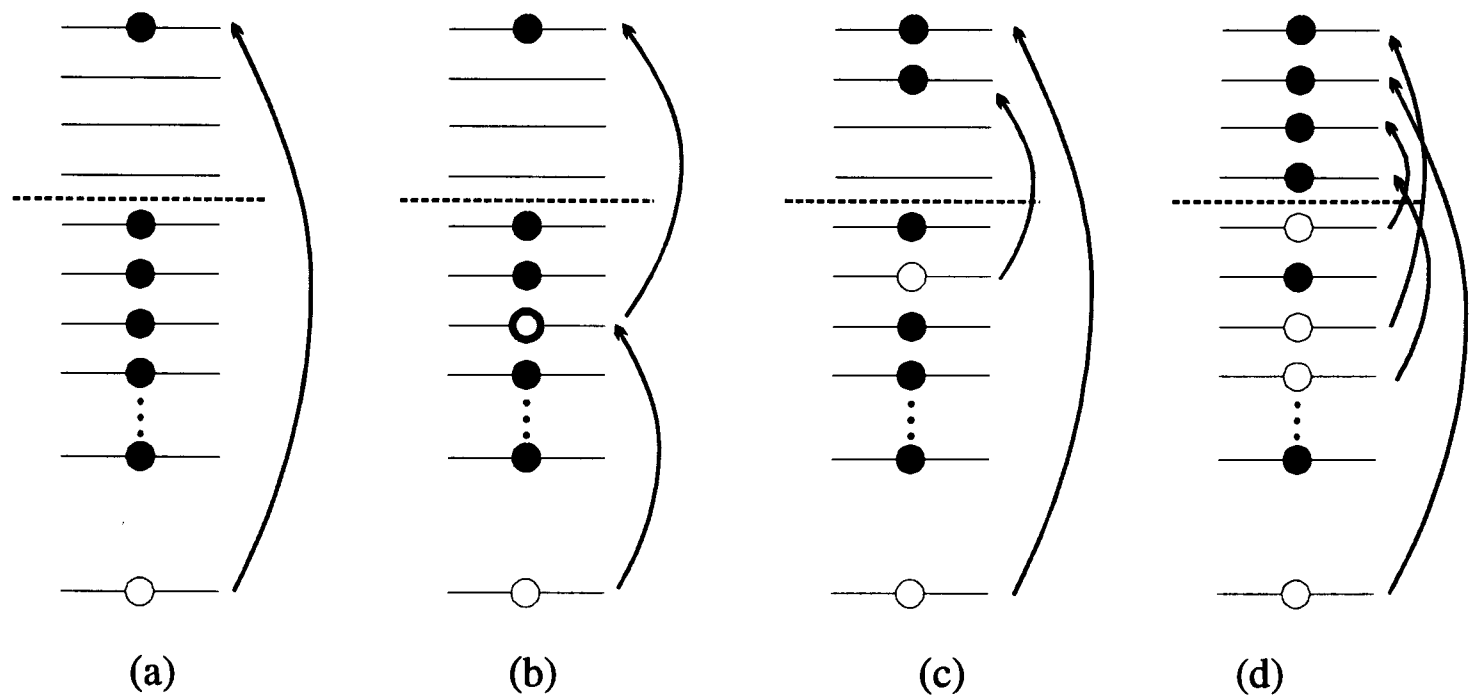


Figure 7.2: *Rearrangement processes accompanying the photoexcitation of an electron from the valence band to a level above the Fermi level: (a) direct process (b) replacement process (c) shakeup process (d) general complex process. The dashed line indicates the Fermi level for the N electrons.*

later be expanded to a three band model when the experimental results are discussed.

A degenerate 1D gas of N electrons initially in equilibrium is perturbed by an absorption process in which an electron is photoexcited into the conduction band and leaves behind a hole in the valence band. The sudden appearance of the hole potential leads to a collective response of the $N+1$ electrons in the Fermi sea, which is twofold: First, the correlation of the electrons around the hole potential leads to a dynamical self-energy of the hole and, secondly, the scattering cross section for electrons at the Fermi edge with the hole is strongly enlarged. This is due to the fact that electrons at the Fermi surface can correlate and rearrange more efficiently than electrons in the Fermi sea. The electrons scatter either through direct transitions from above the Fermi surface accompanied by a rearrangement of the background electrons (fig. 7.2) or through transitions mediated by electrons within the

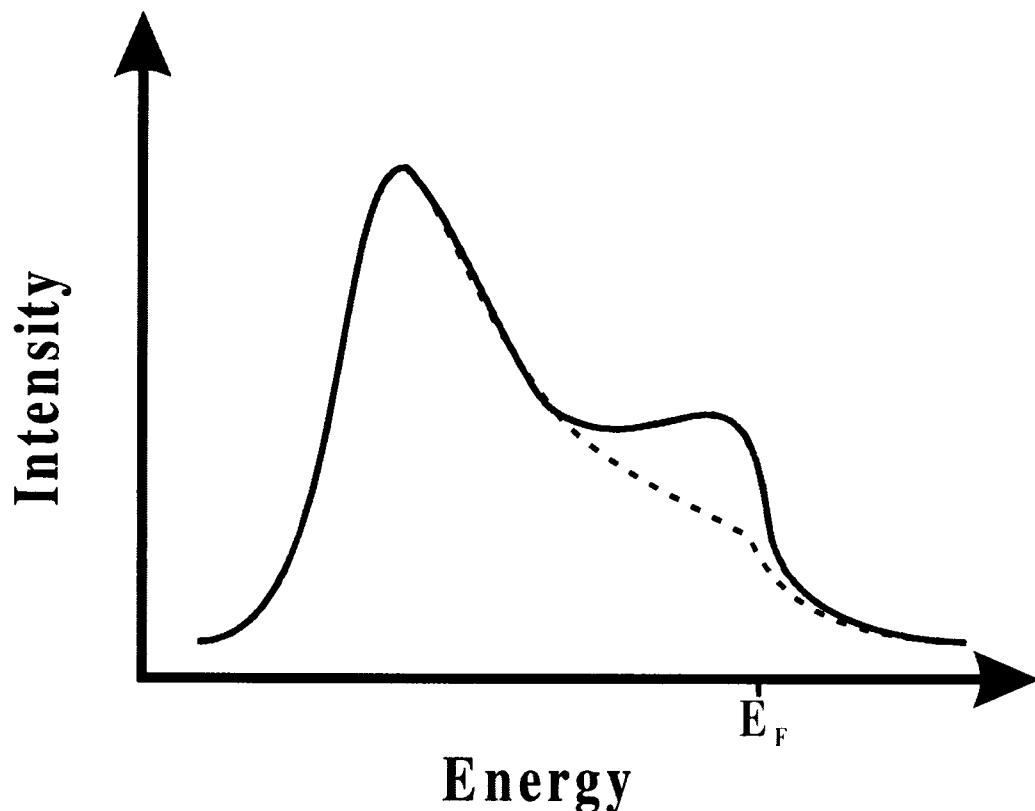


Figure 7.3: Schematic emission spectrum showing the effect of a Fermi edge singularity (FES). The dashed line shows the absorption spectrum without a FES while the spectrum drawn with the straight line includes the recombination enhancement due to a FES.

Fermi sea, the so called “replacement transitions” [Friedel 1969].

The strong recombination rate at the Fermi edge leads to a power-law anomaly in optical spectra. The optical absorption spectrum $I(\omega)$ in the vicinity of the absorption edge E_F behaves as $I(\omega) = b\omega^\beta$, with the critical amplitude b and a ω -independent critical exponent β , where $\omega \geq 0$ corresponds to a photon energy measured from the Fermi edge. In case of a singularity the exponent $\beta < 0$ and shows as an enhancement of the recombination intensity in the absorption and emission spectra (fig. 7.3).

To satisfy the k -conservation for optical transitions of Fermi edge electrons, holes with wavevectors of k_F are required. In 2D and 3D systems with mobile holes, there are no singularities due to peak broadenings produced by indirect transitions from the top of the valence band to the Fermi level accompanied by low-energy excitations of the Fermi sea to

ensure momentum conservation. Only by strong spatial localisation of the hole, which results in large wavevector component in the hole wavefunction can the k-conservation can be fulfilled and FES be observed.

In 1D the broadening mechanism is not efficient because allowed low-energy excitations have either 0 or $2 k_F$ momentum. Therefore, the FES in 1D is much stronger and sharper than in 2D and makes 1D systems good candidates for presenting singularities even for cases with mobile holes [Müller 1992, Calleja 1991].

7.3 FERMI EDGE SINGULARITIES IN PHOTOLUMINESCENCE SPECTRA

The PL measurements in figure 7.4 were made at 8 K using Ar^+ laser excitation at 2.4 eV. They were taken from a series of samples B1-B3 with nominally identical structural parameters but different dopant densities¹.

The nominally undoped sample B1 shows sharp excitonic peaks labelled $n = 1, 2$ with full widths at half maximum (FWHM) of 6 and 8 meV respectively. Sample B3 shows the effect of modulation-doping on the structure when the Fermi energy lies just above the $n = 2$ band bottom. Like the undoped sample it shows recombinations from the first two levels, but doping strongly suppresses the $n = 1$ intensity. However, in addition sample B3 shows a distinct peak above $n = 2$ which has the characteristics of a pronounced Fermi edge singularity. The electron density inferred from the PL spectrum of B3 is $\sim 1.5 \times 10^6 \text{ cm}^{-3}$.

7.4 TEMPERATURE DEPENDENCE

A strong characteristic of the FES is its temperature sensitivity as the many body effect is

¹ For a detailed analysis of the basic PL features in samples B1-B3 refer to chapter 5 and 6.

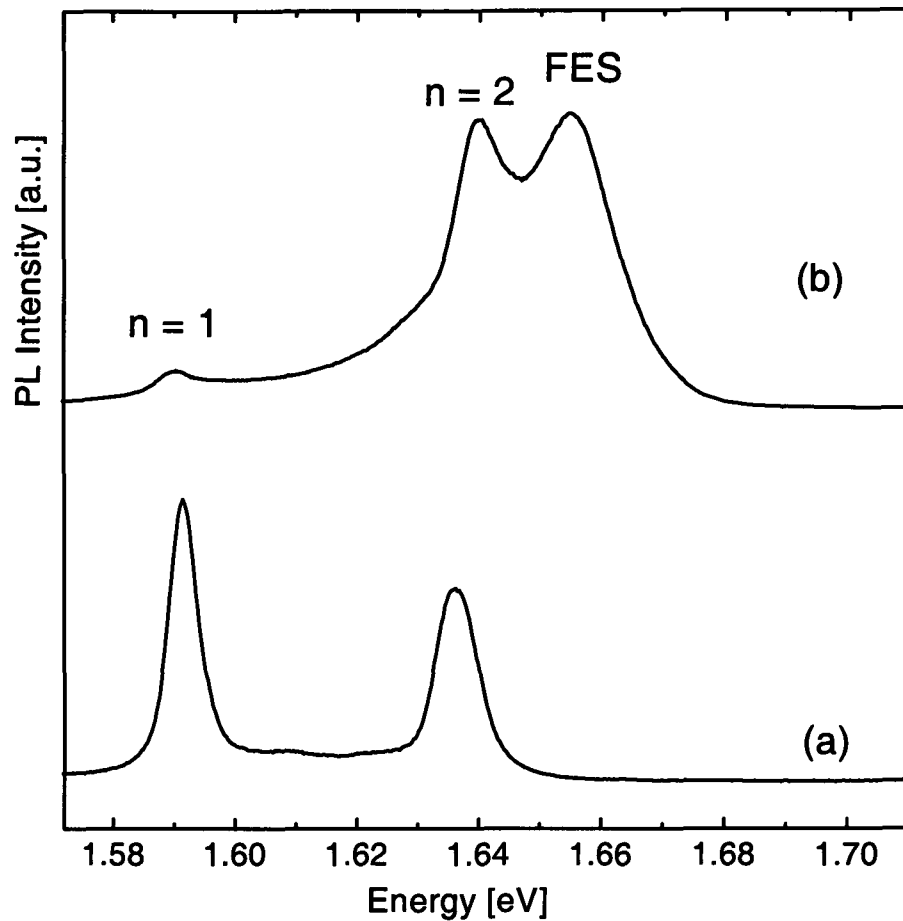


Figure 7.4: *Fermi edge singularity in photoluminescence spectrum of the doped sample B3. (a) shows the wire luminescence of the undoped sample A1 with the transitions from $n = 1$ and 2. The luminescence from heavily doped sample A3 in (b) exhibits a strong singularity at the Fermi edge due.*

highly dependent on a sharp Fermi surface. When the sample temperature is increased from 8 to 20 K, the PL spectra show a rapid quenching and broadening of the FES (fig. 7.5). By 20 K the peaks of the QWR states have not decreased significantly, but the sharp singularity has diminished to a barely resolvable shoulder. The strong sensitivity of the FES intensity on the temperature is consistent with observations in other QWRs structures [Schmitt-Rink 1986, Ruckenstein 1987, Skolnick 1987, Ohtaka 1989, Uenoyama 1990, Fritze 1993] and theoretical predictions [Rodriguez 1993 and 1994]. The heating leads to the shake up of the sharp Fermi surface and effectively breaks the collective correlation of the electron gas with the hole potential.

Similar behaviour was observed when the electron temperature was increased by applying a

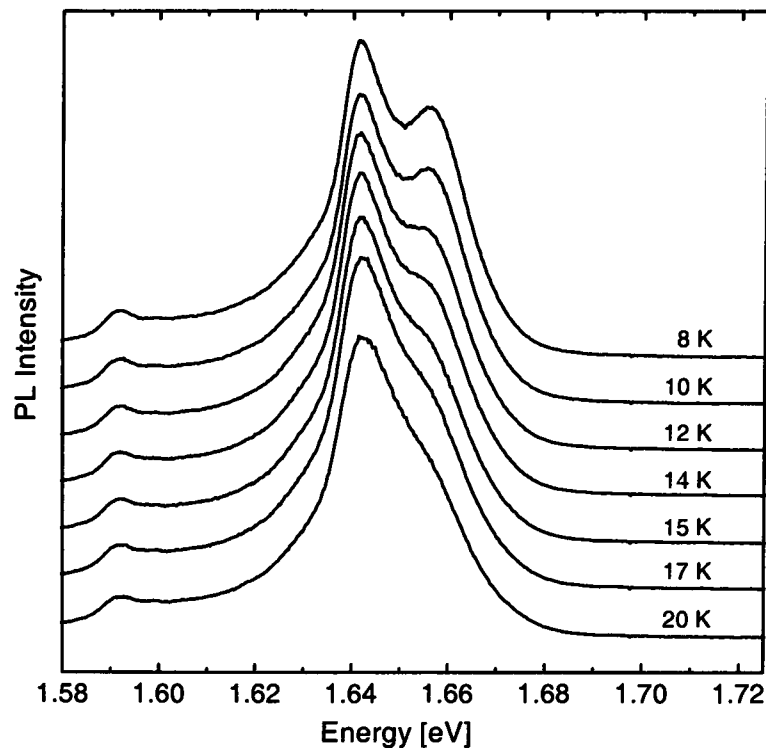


Figure 7.5: *Temperature dependence of the Fermi edge singularity (FES) in the photoluminescence spectrum. The FES washes out rapidly with increasing lattice temperature due to the smearing of the Fermi edge. The temperature sensitivity is a strong characteristic of the FES.*

voltage to the wires. The excitation laser and the voltage were simultaneously pulsed with a pulse width of $2\ \mu\text{s}$ and a duty cycle of 0.95 to avoid lattice heating. Optical spectra for the sample B3 are shown in Fig. 7.6, where we find that the FES is extinguished when only 6 V is applied. At this point the power dissipation is $5 \times 10^{-3}\ \text{W}$, and the electron temperature is estimated to be 46 K [Schwarz 1999]. At voltages above 6 V the band edge recombination blue-shifts due to strong electron heating.

Finally, the optical transitions were studied under high excitations powers. With increasing excitation levels (fig. 7.7), the FES is rapidly quenched, although enhancement at the Fermi energy seems to persist to the highest intensity. This can be understood in terms of two competing processes. The quenching is again due to Fermi surface smearing while the persistence of the FES is due to the equal amounts of high density electrons and holes photocreated which ensures k conservation. Calleja et al. [1991] also found in calculations

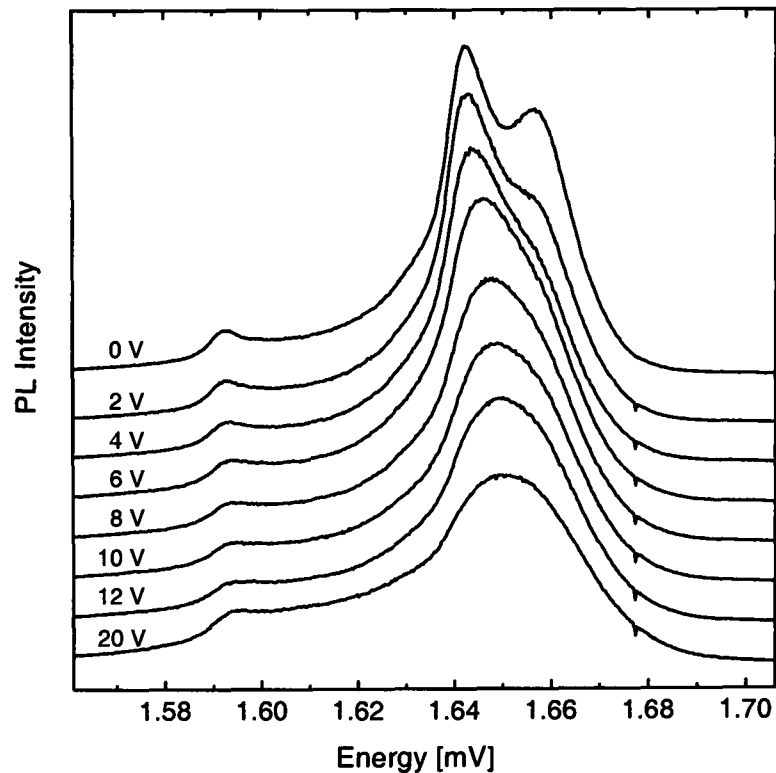


Figure 7.6: *Effect of electron heating on the Fermi edge singularity.*

Photoluminescence spectra taken at increasing applied voltages along the wire show again the strong reduction of the FES due to Fermi edge smearing.

that the FES in 1D does not disappear at high electron concentrations due to similar considerations.

7.5 FERMI EDGE SINGULARITY IN A MAGNETIC FIELD

The application of a transverse magnetic field gives further information about the form of the 1D confining potential (cf. chapter 5.4 and 6.3) and the origin of the FES. Figure 7.8 a shows the variation of the PL spectrum for $\mathbf{B}$ applied perpendicular to the sample surface. At low fields, the $n = 1$ and $n = 2$ lines shift only slightly which is expected due to the lateral confining potential. Assuming parabolic confinement, the electron energy is $\hbar\omega \sim (\hbar\omega_0^2 + \hbar\omega_c^2)^{1/2}$ where ω_0 is the effective oscillator frequency and ω_c is the cyclotron frequency, so that only a weak quadratic $\mathbf{B}$ -dependence arises at low field. When $\mathbf{B}$ is applied in the orthogonal direction, transverse to the wire and in the plane of the sample, so that the lateral

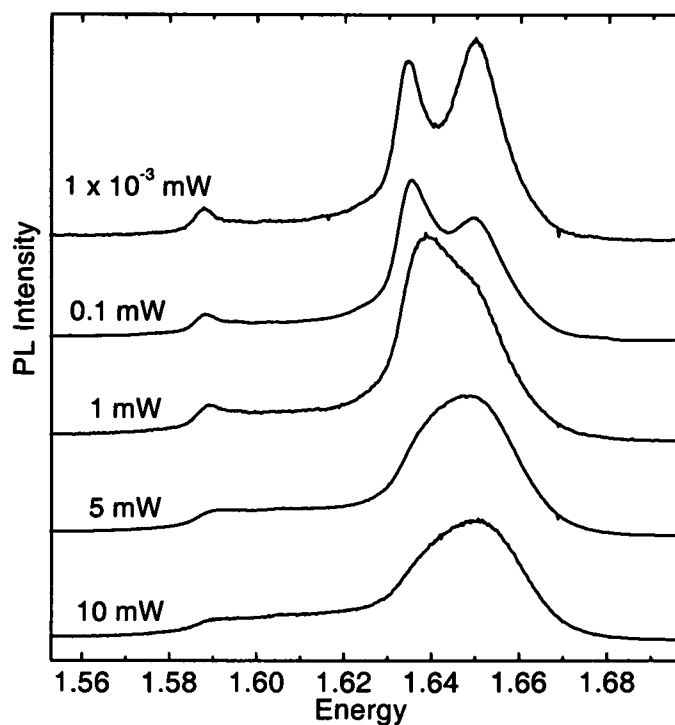


Figure 7.7: *Effect of increased photoexcitation powers on the Fermi edge singularity (FES). The FES decreases with increasing carrier temperatures as seen in fig. 7.5 and 7.6, however persists at higher powers due to high carrier densities.*

confinement is produced by the AlGaAs quantum well barriers, the energy shift is even smaller due to the stronger confining potential. The energy shift of the FES is also small (fig. 7.8 b) and is consistent with the small diamagnetic shifts observed by Fritze et al. [1993].

However, when $\mathbf{B}$ is perpendicular to the QWRs, the FES increases significantly in intensity with increasing field. This result is similar to that reported by Chen et al. [1990] who observed strong enhancement of the FES in quantum well structures due to interference between the $n = 1$ and $n = 2$ subbands. He investigated the influence of a 2D electron gas with the Fermi level close to the $n = 2$ conduction subband under a magnetic field and observed an enhancement of the FES at the crossing of the $n = 1$ Landau level with the $n = 2$ magneto-exciton. Müller [1990 and 1992] developed a model of such a system and found the FES to be strongly enhanced due to a hybridisation between the Fermi edge resonance and

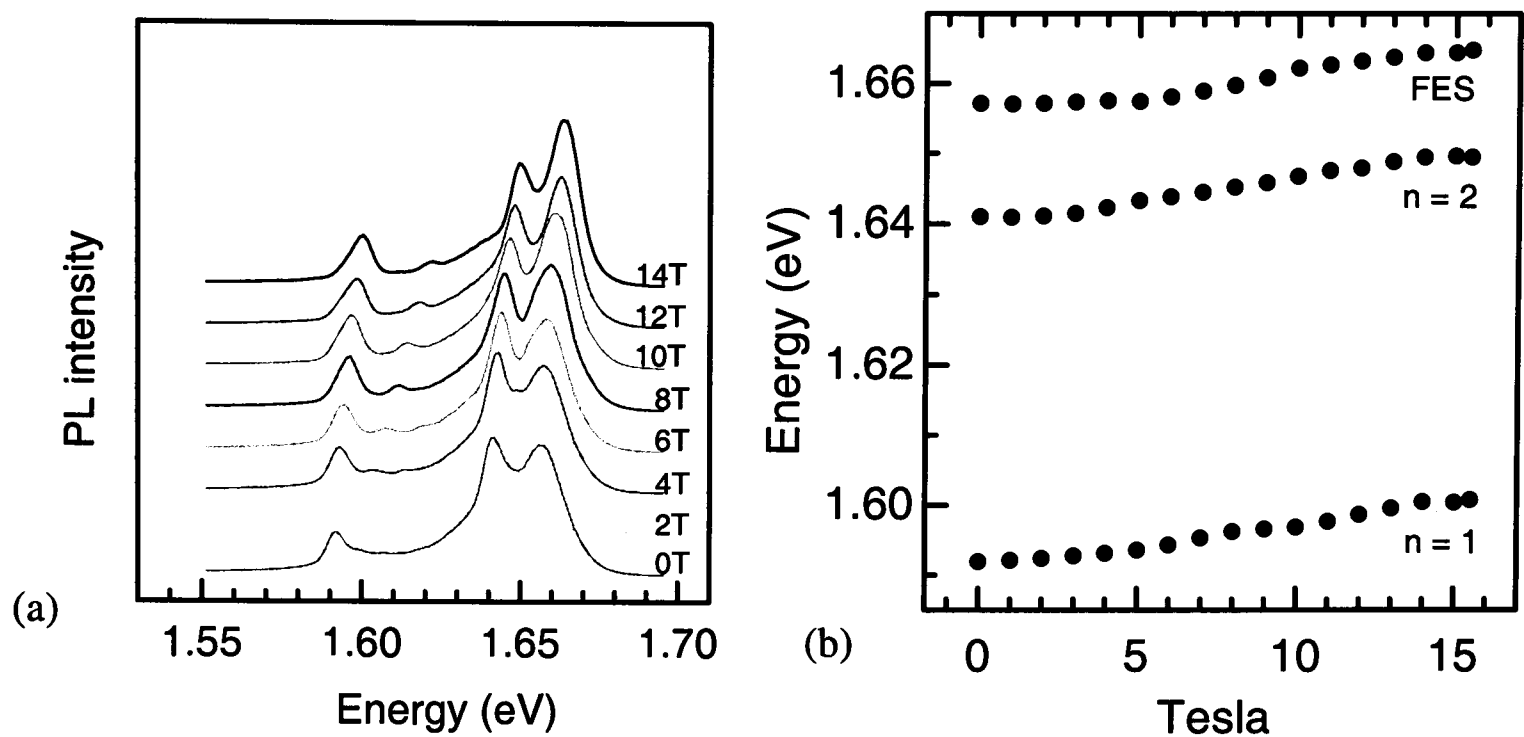


Figure 7.8: *Behaviour of Fermi edge singularity in an applied magnetic field perpendicular to the sample surface. The peaks blueshift only weakly with an increasing field, however, the Fermi edge singularity increases clearly in intensity due to band coupling.*

an excitonic resonance in the subband above. This band coupling comes from the breaking of the symmetry of the confining potential [Rodriguez 1994a]. With increasing magnetic fields this asymmetry grows stronger and therefore results in a stronger FES.

7.6 DISCUSSION

A much discussed issue of FES in low dimensional systems is whether hole localisation is required. The PL linewidths for our samples are ~ 6 meV, and most likely arise from interface fluctuations or doping defects. Hawrylak's calculation for a quasi-1D system in a parabolic confining potential indicate that for such localised holes the oscillator strength is strongly enhanced at the Fermi edge [Hawrylak 1992]. However, the Coulomb attraction can

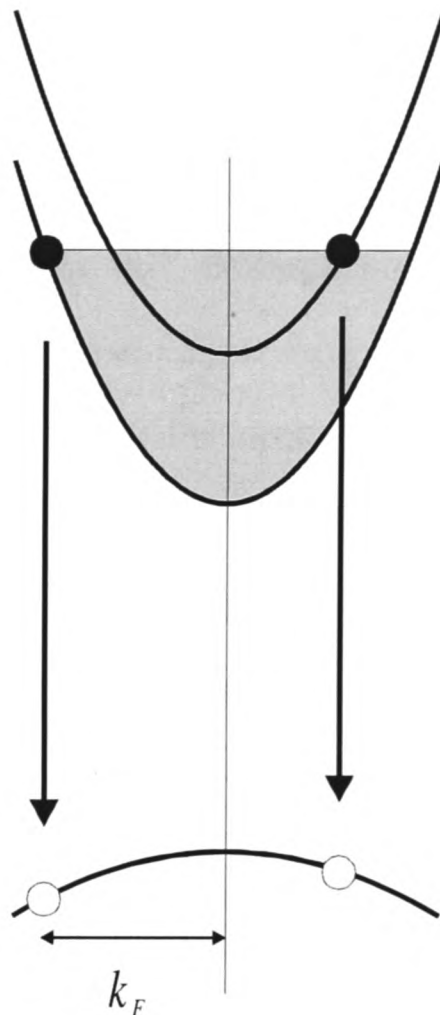


Figure 7.9: *Three band model for Fermi edge singularity (FES) occurring in a degenerate 1D system with two occupied subbands. In this case both subbands contribute to the FES while the recombinations from the second subband require hole with smaller wavevectors than the ones from the first subband.*

also be stronger in narrow wires (< 6.5 nm), so that localisation of holes may not be necessary for the observation of a strong FES [Rodriguez 1993]. Models using the Tomonaga-Luttinger liquid conclude that the critical exponent which governs the recombination enhancement at E_F is even independent of hole dynamics [Ogawa 1992].

The occupancy of two subbands in sample B3 complicates the modelling of the many body processes which lead to the FES. However, the study of such systems is particularly interesting in two respects: the additive contributions from each subband and the band

coupling. Both subbands contribute to the singularity as depicted in figure 7.9 and therefore can result in stronger singularities than in wires in the absolute quantum limit. Rodriguez and Tejedor [1993] investigated the individual contributions from $n = 1$ and 2 in a three-band model. They come to the conclusion that although it is difficult to determine the exact contributions it can be estimated that the FES is more related to states in the first subband than in the second one. The elements of the optical matrix which are derived within the model indicate that a polarization dependence exists; in experiments this could give some information about the ratio between the intensities of the $n = 1$ and 2 transitions.

The second aspect for which systems with more than one occupied subband are studied is the coupling of the bands which have been found to increase the FES intensity significantly [Rodriguez 1994a, Müller 1990, Chen 1990, 1991]. This effect is expected to be stronger when a magnetic field creates or enhances an asymmetry, which is required for the band coupling [Rodriguez 1993]. The application of the magnetic field on sample B3 confirms this and will be presented later. However, the strong FES seen in sample B3 could indicate an asymmetry of the confining potential in the v-groove QWR. A deviation from a perfectly shaped v-groove, could for example be induced by slightly different growth behaviour on the two different (111) facets of the V.

Another question which remains unresolved by the theoretical models developed so far is the difference between the relative intensities of the optical transitions. Only small singularities from the band bottom are observable for $n = 1$ in sample B3, but also in experimental results of others [Fritze 1993, Skolnick 1987, Calleja 1991]. On the contrary in calculated emission spectra transitions from the band edge are significantly stronger than from the Fermi edge. Skolnick achieves to fit his PL data by using infinite hole masses [fig. 7.10], which would be an unrealistic assumption for sample B3. Calleja suggests that wire width fluctuations result in a reduction of the $n = 1$ peak, but this would only be, at most, a factor of 2 [Rodriguez 1993]. The sharp peaks in the undoped sample B1 indicate also low

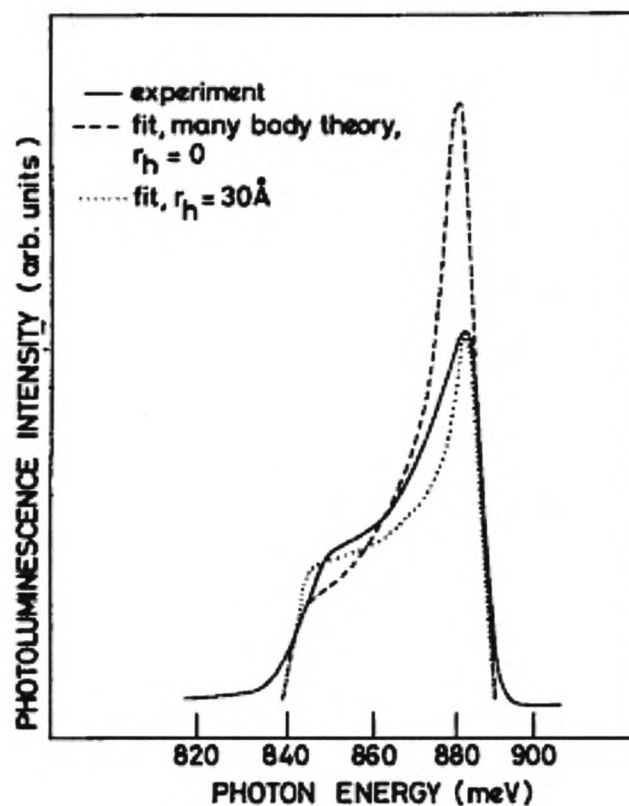


Figure 7.10: Photoluminescence spectrum of a quantum well with a Fermi edge singularity (FES), fitted with a many body model [Skolnick 1987]. An appropriate fit is only achieved when an infinite hole mass is assumed. However, the role of the hole for the FES is controversial and difficult to determine.

structural disorder. Maybe the effects of the random potential arising from ionized donors in the barrier are significant.

When simulating realistic emission spectra, one refining aspect could be the integration of electron-hole Coulomb correlation effects which lead to a suppression of the singularity from the emission edge as studied by Rossi [1996]. As considered in chapter 5 such effects could play a role in the inversion of the intensities ratio of the $n = 1$ and $n = 2$ peaks in the undoped sample B1, when the carrier concentration is increased by varying excitation power.

7.6 CONCLUSION AND OUTLOOK

The results presented here provide the clearest evidence of a Fermi edge singularity in the PL spectrum of a degenerate 1DEG to date:

- The strongly doped sample with an electron density of $1.5 \times 10^6 \text{ cm}^{-1}$ exhibits transitions from $n = 1$ and $n = 2$ and a well pronounced FES.
- Although FES should be more defined in 1D systems for free holes than in 2D or 3D, the strong enhancement of the singularity over the $n = 1$ density of states peak is strongly suggestive of weak hole localization.
- The two subbands in sample B3 contribute both to the intensity of the FES by an additive as well as a coupled component. In a transverse magnetic field the band coupling and therefore the FES is enhanced.
- It remains unclear why the $n = 1$ transition is suppressed. Possibly complicated electron hole correlation effects play a role.
- As expected the FES is highly temperature sensitive. This has been shown through lattice and electrical heating. At high excitation powers the FES is reduced as well, but remains persistent due to high electron hole densities.

CHAPTER 8

HOT ELECTRONS IN MODULATION-DOPED V-GROOVE QUANTUM WIRES

CONTENTS

8.1	INTRODUCTION	131
8.2	TIME-RESOLVED PHOTOLUMINESCENCE EXPERIMENTS	132
8.3	ELECTRO-PHOTOLUMINESCENCE EXPERIMENTS..	137
8.4	CONCLUSIONS AND OUTLOOK.....	147

8.1 INTRODUCTION

Hot electrons have long been studied in bulk and low-dimensional semiconductors. The earliest publications go back to the 1930's which discussed the electrical breakdown in insulators, the so-called dielectric breakdown [Zener 1934, Fröhlich 1937]. In more recent years, the prediction of Bloch oscillations and associated negative differential resistance (NDR) in a superlattice miniband by Esaki and Tsu [1970] created a strong interest in hot electrons in low-dimensional semiconductors. The investigation of transport phenomena has led to the fabrication of structures with ultra-high mobilities through modulation-doping and the discovery of a novel mechanism for NDR - real space transfer [Hess 1979, 1998].

The usage of optical spectroscopy has played an important role in investigating the details of hot carrier relaxation and carrier transport. Optical techniques provide a means for determining the carrier distribution function (DF), opposed to electrical transport measurements (cf. chapter 6.4) which only measure the average over the entire carrier DF. A major advantage of all-optical methods is that in conjunction with ultra-short laser pulses they represent efficient tools in analysing the dynamics of hot carriers. For example, scattering rates have been measured by using pico- and femtosecond laser spectroscopy by Ryan et al. [1988] (see also review by Kash et al. [1991]).

In this chapter time-resolved measurements of modulation-doped v-groove QWRs will be presented investigating the relaxation of hot carriers. The experiments reveal that recombination lifetimes in doped structures can be significantly increased. It is proposed, that this is mainly due to electron-hole separation caused by the dopant layer as well as the pinch-off between the QWR and SQW. Furthermore, the luminescence decay times in different QWR subbands of highly doped samples is analysed.

In a combined electro-optical experimental set-up electrons can be efficiently heated in an applied electric field and only a low photoexcitation power is used to probe the system. In contrast to all-optical methods, this strongly reduces the number of photocreated holes,

which simplifies the analysis of electron DFs and allows quantitative statements about *electron* energy loss rates (ELR). Using electro-PL (EPL) experiments important information about electron energy loss mechanisms and transport channels in samples A2 and B3 were obtained. Real-space transfer from the QWR to the SQW was observed, and LO phonon scattering was established for the first time as the main relaxation process for hot electrons above ~50 K in v-groove QWRs.

8.2 TIME-RESOLVED PHOTOLUMINESCENCE EXPERIMENTS

The dynamics of carrier relaxation in undoped etched QWRs [Mayer 1990, Kohl 1990, Cingolani 1991] as well as v-groove QWRs [Maciel 1995] have been investigated in the past. In etched QWRs the relaxation was found to be slower than in the starting QW material, and the screening of the electron-LO-phonon interaction and hot phonon effects were proposed as possible causes. Also in v-groove QWRs it was observed that cooling is slow, however, Monte Carlo simulations confirmed the significance of the hot phonon effect in reducing the cooling rate at high densities.

The following time-resolved PL measurements were performed on the two modulation-doped v-groove QWR samples C and A2, already discussed in chapter 6. The decay of the luminescence in the QWR and SQW was investigated with picosecond resolution; with a laser pulsewidth of ~100 fs a system time resolution of ~30 ps was achieved (cf. chapter 4.3). The samples were cooled at 4 K and the estimated carrier density was $3 \times 10^6 \text{ cm}^{-1}$.

Figure 8.1 shows the lifetime measurements of sample C which has a nominal quantum well width of 10 nm, and therefore has a relatively small confinement energy (cf. chapter 6.2). A Ti-sapphire laser was employed to excite the structure below the confining barrier and above the SQW and the QWR band-gap. The continuous wave (cw) PL spectrum (solid curve) shows the two peaks of the SQW and the QWR at 1.548 eV and 1.570 eV. Furthermore, the intensities of the time-resolved measurements are summarized for various times between

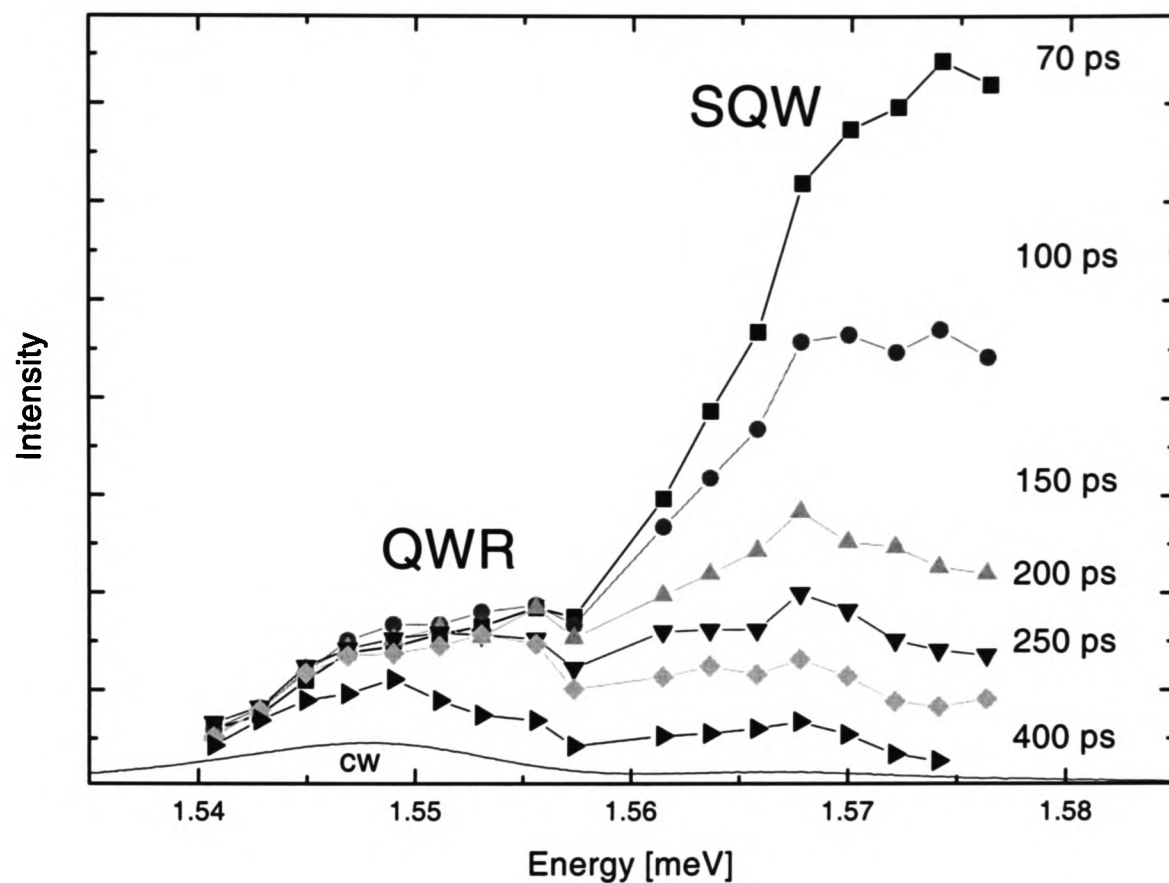


Figure 8.1:. *Time-resolved photoluminescence of the quantum wire (QWR) and the side quantum well (SQW) in sample C. The figure shows the summary of time-resolved measurements taken at different wavelengths for various times after photoexcitation of 70 – 400 ps. It can be observed that the decay in the QWR is much slower than in the SQW. A continuous wave (cw) spectrum is shown as reference.*

70 – 400 ps after the excitation. It is striking that after 400 ps the luminescence in the SQW has almost disappeared, while in the QWR it persists over the same time scale.

As it can be seen in figure 8.2 the luminescence decay time in the SQW is about 190 ps which is determined by the times for recombination and trapping into the wire. The carrier decay time in the QWR, however, is a factor of three longer (~657.9 ps).

A decay time of several hundred picoseconds is typical for a high-quality 2D system, but the long lifetime in the QWR is indicative of a reduced radiative recombination efficiency. The cause for this could originate from the geometry of the sample. Due to the potential difference in the SQW and QWR, carriers generated or trapped in the SQW will be spatially

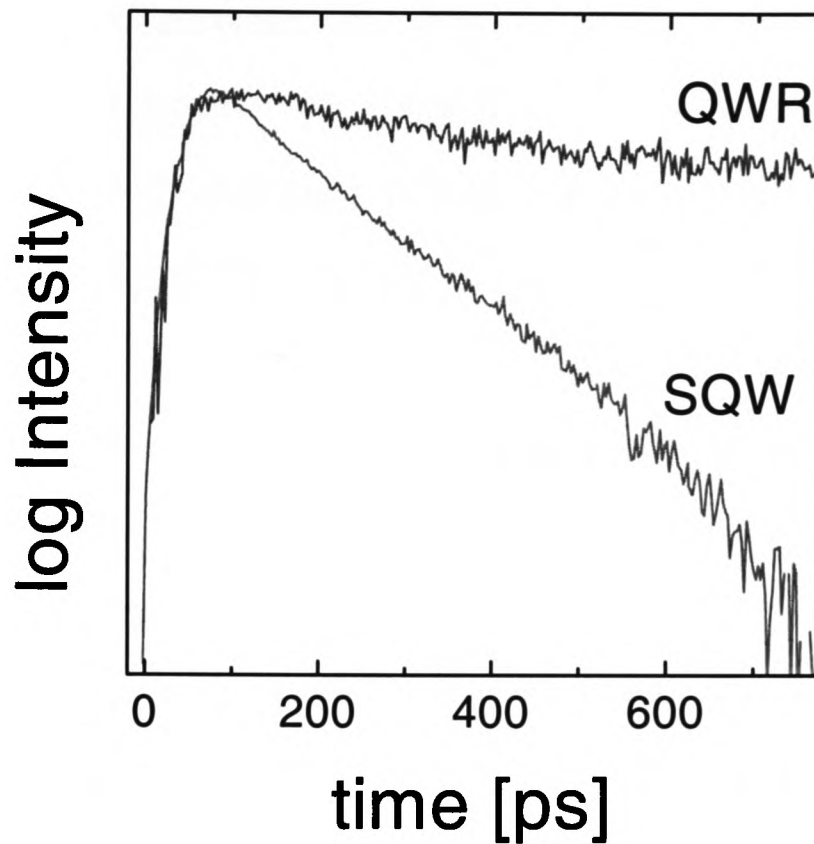


Figure 8.2: *Decay of quantum wire (QWR) and side quantum well (SQW) luminescence in sample C. The lifetime of 190 ps in the SQW is typical for high quality quantum wells. The lifetime in the QWR, however, is three times longer, indicating a reduced radiative recombination efficiency.*

transferred into the wider wire. However, to do so, the carriers have to overcome the potential barrier created by the pinch-off between the 1D and 2D region, which is more significant for electrons than for holes. This leads to a separation of holes and electrons and a reduced spatial overlap of the corresponding wavefunctions. Hence, the radiative recombination lifetime is prolonged.

An alternative explanation was given by Oberli et al. [1999], who have studied the effect of disorder on the radiative properties of semiconductor QWRs. They come to the conclusion that long carrier lifetimes in the QWR can be due to carriers localised by disorder.

The effect of increased recombination lifetimes due to separation of holes and electrons could be enhanced by the phenomenon observed in excitation power dependent PL measurements of the same sample (cf. chapter 6.2). A strong blue-shift of the QWR luminescence peak occurs with increasing excitation power. This was explained by carrier separation due to the trapping of electrons at positively charged donor ions. The holes move into the QWR and reduce the electron density in the 1DEG which leads to a reduction in the band bending and subsequently to an increase of the transition energy. The combined effects of carrier separation due to the pinch-off and the electron trapping could cause the unusually long QWR luminescence lifetimes in sample C.

Figure 8.3 shows the decay of the luminescence of sample A2, when only the QWR is excited, i.e. when the excitation energy is below the SQW energy (cf. chapter 6.2). The bottom curve represents again the cw PL of the sample. The other spectra show the time dependence of the carrier population in the different subbands of the QWR. The time-resolved spectra for the states $n = 1, 2$ and 3 in figure 8.4 show that the highest subband decays most rapidly with a lifetime of 238 ps, comparable to that of a QW, while the $n = 2$ level luminescence is relatively long-lived (~ 390 ps). Additionally a plateau can be observed for the first ~ 100 ps similarly to the measurements by Ambigapathy et al. [1997] where the lower subbands exhibit constant PL intensities for ~ 150 ps while the higher subbands have not decayed significantly. This can be explained by carrier filling from higher subbands

The $n = 1$ luminescence decay shows three time regimes with different exponential decay constants: (a) < 150 ps where the intensity again remains almost constant, (b) $150 - 300$ ps with $\tau = 448$ ps and (c) > 300 ps with $\tau = 1536$ ps. While the first phase is dominated by carrier filling from higher subbands, in the second phase recombination becomes stronger. As the Fermi level lies just above the $n = 3$ subband energy, the long lifetime of the third phase is due to relaxation of photoexcited holes. This is primarily by phonon scattering as the carrier-carrier (c-c) intersubband relaxation is an inefficient process and c-c scattering in

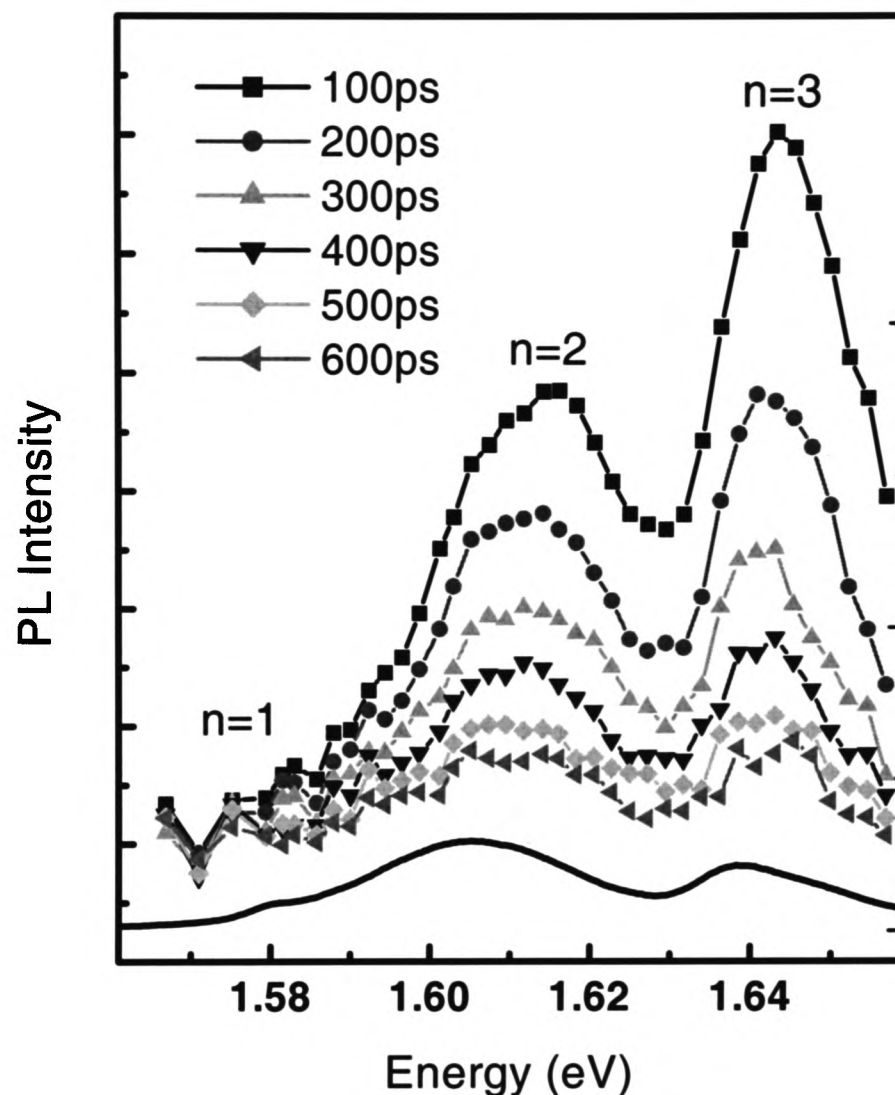


Figure 8.3: Time-resolved photoluminescence from all quantum wire states ($n = 1, 2, 3$) in sample A2. Lifetimes are longer in lower subbands probably due to cooling of a thermalised electron-hole system, given the high electron density of $3 \times 10^6 \text{ cm}^{-1}$. The cw, time-integrated photoluminescence spectrum is shown as reference (solid line, no symbol).

1D is modified, such that c-c intraband process cannot occur in wires¹. Although hole intersubband relaxation is likely to be slow (on the ns timescale) due to the small energy level separation in sample A2, the population relaxation observed here is probably due to the cooling of a thermalised electron-hole system, given the high electron density ($\sim 3 \times$

¹ This is due to the fact that in 1D only two states in each subband for a given energy are allowed, k_x and $-k_x$, as discussed in chapter 7.2.

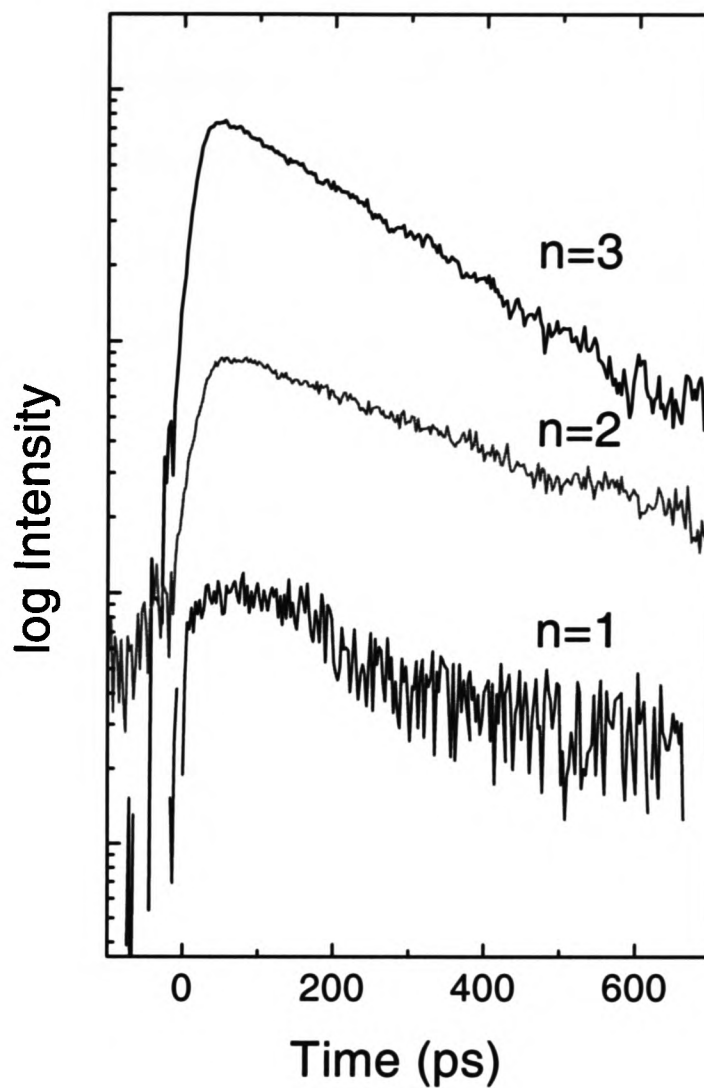


Figure 8.4: *Decay of quantum wire luminescence from different states ($n = 1, 2, 3$) in sample C. The decay time of the $n = 3$ subband recombination is ~ 238 ps, whereas the decay times from the $n = 2$ subband is around 380 ps. The decay of the $n = 1$ luminescence exhibits three time regimes.*

10^6 cm^{-1}). A detailed Monte Carlo simulation along the lines described by Rota et al. [1995] would help to clarify this issue.

8.3 ELECTRICAL FIELD HEATING OF ELECTRONS

All-optical studies as the time-resolved measurements presented in the previous section allow important insights into the relaxation process of hot carriers. In particular, they provide the best means of determining the carrier distribution functions (DFs). However, the heating of carriers by the means of photoexcitation leads to the creation of equal number of holes

and electrons. The luminescence spectrum is then determined by the DFs of both holes and electrons, and it can be approximated by $L(\hbar\omega) \approx \alpha_0(\hbar\omega)f_e f_h$, where f_e is the DF of the electrons, f_h the DF of the holes and α_0 the absorption coefficient in the absence of carriers. Therefore, only the product of both DFs can be determined and they can not be determined separately.

A second drawback when using photoexcitation to heat carriers is that it is difficult to obtain quantitative information about energy loss rates (ELRs). In early steady-state studies Shah and Leite [1969] used continuous wave excitation to investigate ELRs of photoexcited carriers. They found that the photogenerated electrons and holes can be characterised by a temperature higher than the lattice temperature and that LO phonons play an important role in the energy relaxation process. However, it was difficult to quantify energy-loss rates (ELR) because they have to be derived from the optical power input into the carriers, a quantity which is hard to determine.

These difficulties can be overcome in a combined electro-optical set-up where a DC current is applied to modulation-doped structures. In these electro-PL (EPL) experiments the majority carriers are accelerated by the electrical field and probed by optical means. The optical excitation is kept sufficiently low, through low power and pulsing, so that it does not heat the lattice. Moreover, in the case of n-doping the number of photocreated holes is much smaller than the number of electrons and thus the electron DF dominates the luminescence. In such experiments it is also easy to determine the power input by measuring I-V characteristics. Such experiments were performed in bulk material by Southgate et al. [1971] and Takenaka et al. [1978] and in quantum wells by Shah et al. [1978, 1983, 1984, 1985]. In the following, the results of EPL experiments will be presented which were performed on modulation-doped v-groove QWRs.

PL samples which feature ~2000 of closely packed, electrically isolated parallel wires with about 4 mm length were equipped with contact pads at each end of the wires and connected to a pulsed electrical power source. While the voltage is applied to the wires, they were

probed with a weak synchronously pulsed Ar laser beam with an energy of 2.4 eV and a power of $< 1 \text{ mW cm}^{-2}$ (cf. chapter 4.4). To investigate the heating of electrons in different parts of the sample structure and to analyse the energy loss mechanisms the EPL data was evaluated in conjunction with temperature dependent PL (TPL) measurements. The carrier, i.e. electron temperature was obtained by comparing the 4 K EPL spectra with zero field TPL spectra.

Figure 8.5 shows TPL and EPL spectra of sample A2 in the energy window covering the transitions in the SQW, the VQW and some additional structure (cf. chapter 6.2). In TPL (fig. 8.5 a) spectra the heating of the electrons can be observed in all parts of the structure: The slope of the high energy side of all peaks changes with increasing temperature. This is due to electrons picking up energy from the heated lattice until they reach a thermal equilibrium. In EPL measurements (fig. 8.5 b) heating is seen only in the SQW and at voltages above 4 V. This demonstrates that electron heating in this energy window occurs only in the SQW whereas in the VQW and other parts of the structure heating is not detected at voltages up to 10 V. Figure 8.6 shows the equivalent TPL and EPL spectra from the QWR region in a waterfall diagram. With increasing lattice temperatures (fig. 8.6 a) the Fermi edge² smears out due to heated electrons and merges into the high energy shoulder of the third subband transition peak at 1.665 eV. A similar behaviour can be observed in EPL spectra. However, in contrast to the SQW an effect of the applied voltage on the QWR luminescence can be observed already at very small voltages. At 4 V the shoulder at the Fermi energy has already disappeared and the lines have broadened and developed high-energy wings which start to overlap into the SQW region.

This demonstrates that at low voltages transport is restricted to the QWR and higher fields are needed to initiate conduction in the SQW. This behaviour is strong evidence for real-space transfer from the QWR into the SQW: when the applied electric field is sufficiently high, electrons in the QWR will gain enough energy to overcome the potential barrier

² Refer to discussion in chapter 6.2 (c).

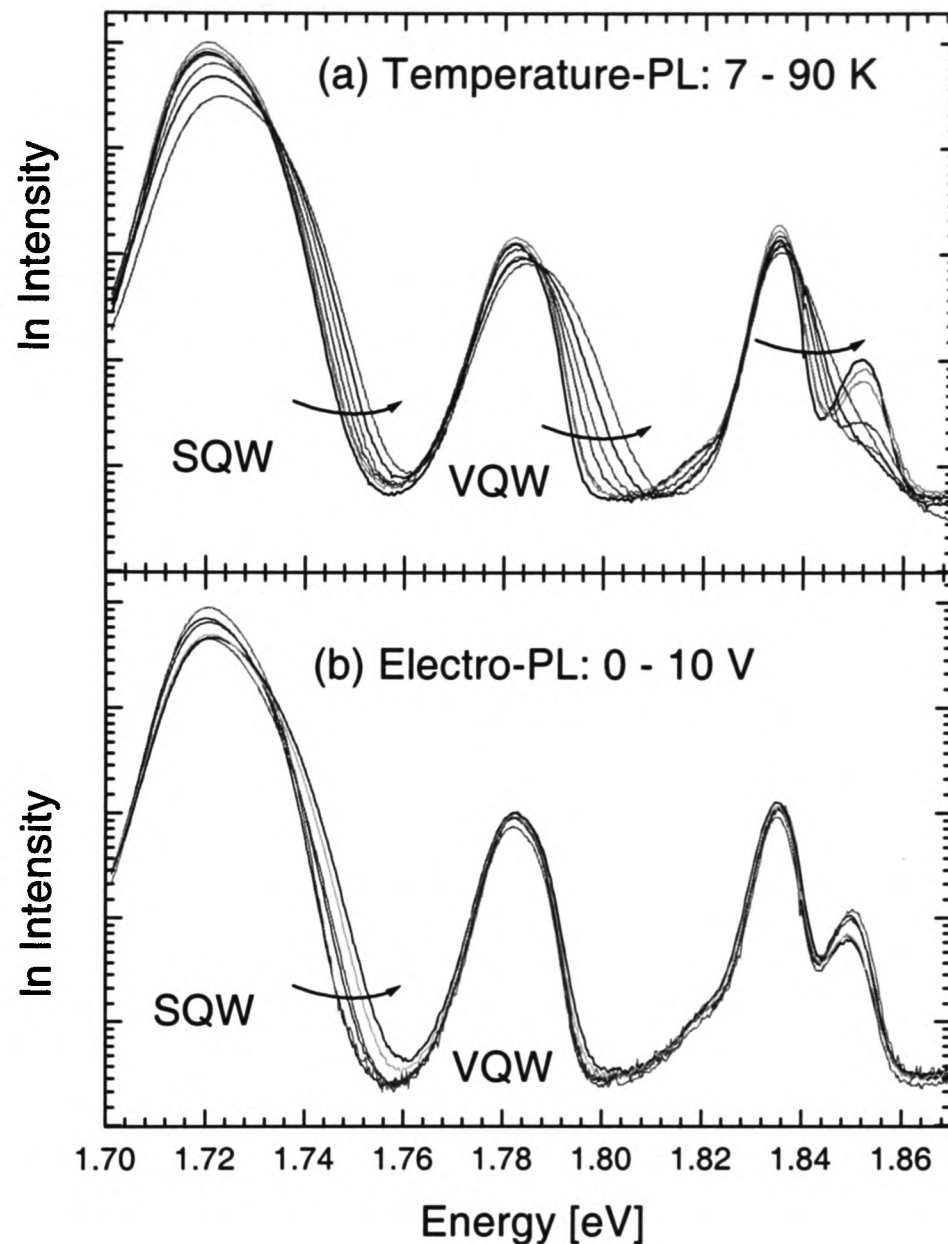


Figure 8.5: *Temperature (TPL) (a) and electro-photoluminescence (EPL) spectra (b) of sample A2 in the side (SQW) and vertical quantum well (VQW) region. (a) With increasing temperature carriers in all areas of the sample structure are heated. (b) EPL spectra show that transport in this energy window only occurs in the SQW and at fields larger than 4 V.*

created by the pinch-off region between the QWR and the SQW. They then transfer into the SQW and contribute to transport in the 2D heterostructure. This behaviour is similar to the calculation of Hess et al. [1979] made in layered heterostructures for conduction parallel to the interface. Hot-electron thermionic emission from high-mobility GaAs into low-mobility $\text{Al}_x\text{Ga}_{1-x}\text{As}$ was proposed as a novel mechanism for negative differential resistance.

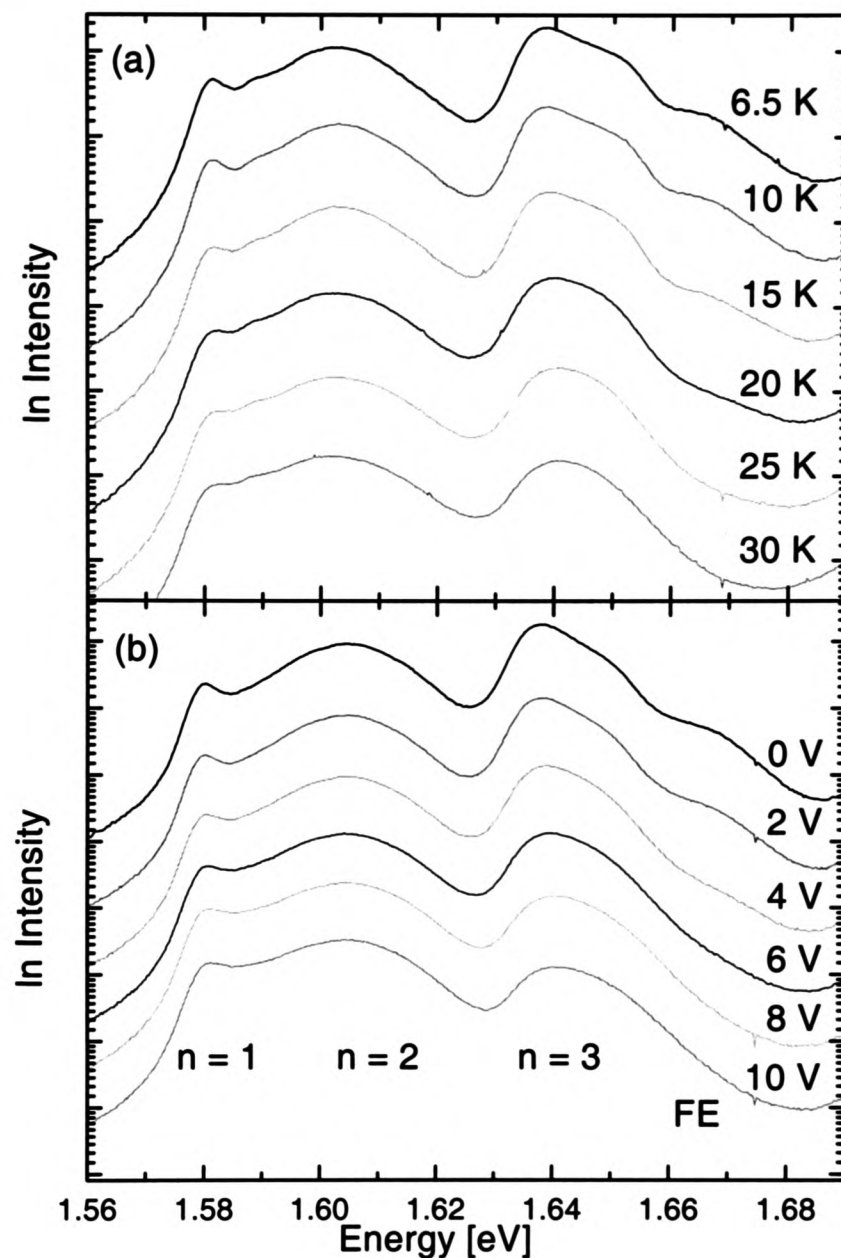


Figure 8.6: *Temperature (TPL) (a) and electro-photoluminescence (EPL) spectra (b) of sample A2 in the quantum wire (QWR) region. The lineshapes of the QWR luminescence in EPL are compared with the lineshapes in the TPL spectra, and temperatures for the carriers in the applied electric field are identified.*

To obtain further information about ELRs, one can make use of the fact that the electrical power dissipated is equal the electron energy loss rate to the lattice in the steady-state condition, assuming the absence of parallel conduction and any contact resistance. The average power loss rate can be defined as [Conwell 1967]:

$$\left\langle \frac{dE}{dt} \right\rangle = \frac{\hbar \omega_{LO}}{\tau_{LO}} e^{-\frac{\hbar \omega_{LO}}{kT_c}}. \quad (8.8)$$

Now, when the inverse of the carrier temperature is plotted as a function of the input power the resulting slope allows quantitative statements about ELRs. This expression is derived within a model, which makes a number of assumptions:

- the energy bands are parabolic
- the carriers have a Maxwell-Boltzmann distribution function characterized by a carrier temperature $T_C > T_L$, with T_C the carrier and T_L the lattice temperature
- the carrier density is high enough to establish Maxwell-Boltzmann carrier distribution, but low enough that screening is not important
- the carrier population is sufficiently low that the effect of Pauli exclusion principle is negligible
- the phonon generation and decay rates are such that a phonon occupation remains low and the phonon occupation number is given by the Bose-Einstein occupation number for T_L

Additionally, for the validity of (8.8) the lattice temperature T_L has to be low (~ 2 K) and the carrier temperature $T_c \gg T_L$.

However, first the input power and the carrier temperatures have to be determined for the voltages used in the experiment. As we know from electrical measurements on wires with different lengths (chapter 6.4) the investigated samples show a reasonable Ohmic characteristic and the I-V curve is linear. During the experiments the currents and voltages were also monitored with standard DC techniques, so that the electrical input power is a well known quantity. The carrier temperatures in EPL spectra were obtained by comparing them with TPL data. As discussed earlier the luminescence lineshape is determined by the electron DF which again reflects the electron temperature. Comparing the lineshapes of the EPL with the lineshapes of the TPL provides the temperatures of the hot electrons at various voltages (figure 8.6). Particularly the slope of the Fermi-edges are used for a comparison as they are

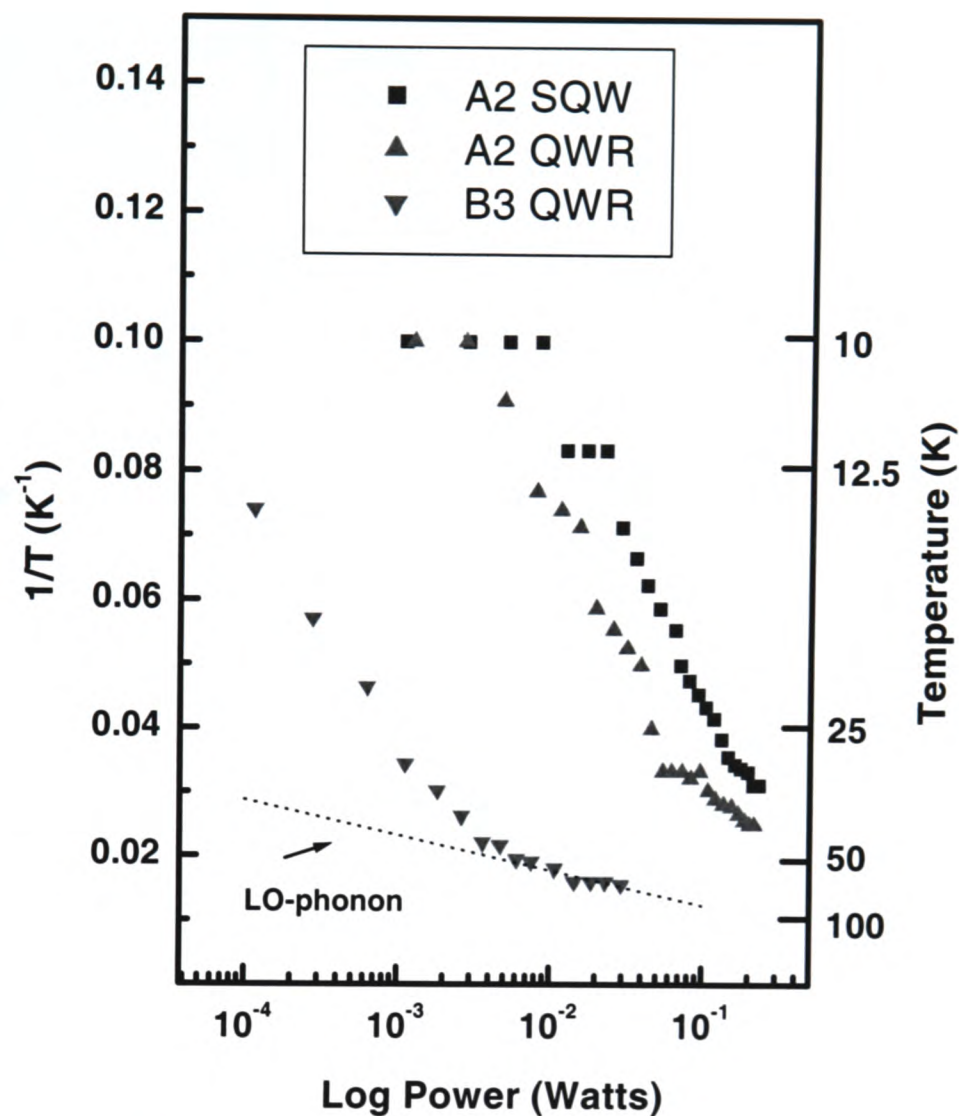


Figure 8.7: Summary of electro-photoluminescence of samples A2 and B2.

The $1/T$ versus power plot shows that in A2 the carriers in the QWR is always hotter than in the SQW. The initially rapid increase in temperature in sample B2 is slowed down by scattering of carriers with LO phonons.

strongly correlated to the lattice temperatures in thermal equilibrium. The resulting accuracy has been found to be at least $\pm 2K$.

Figure 8.7 shows the ELRs for electrons in the SQW and QWR of sample A2 as well as in the QWR of sample B3. As seen before, at low power the heating in sample A2 occurs first in the QWR and the electron temperature increases rapidly. This is consistent with a low ELR due to acoustic phonon scattering (fig. 8.8). Analytical expression for the energy-loss rate, which can be derived from a simple ELR model [Conwell 1967, Nag 1980], show that

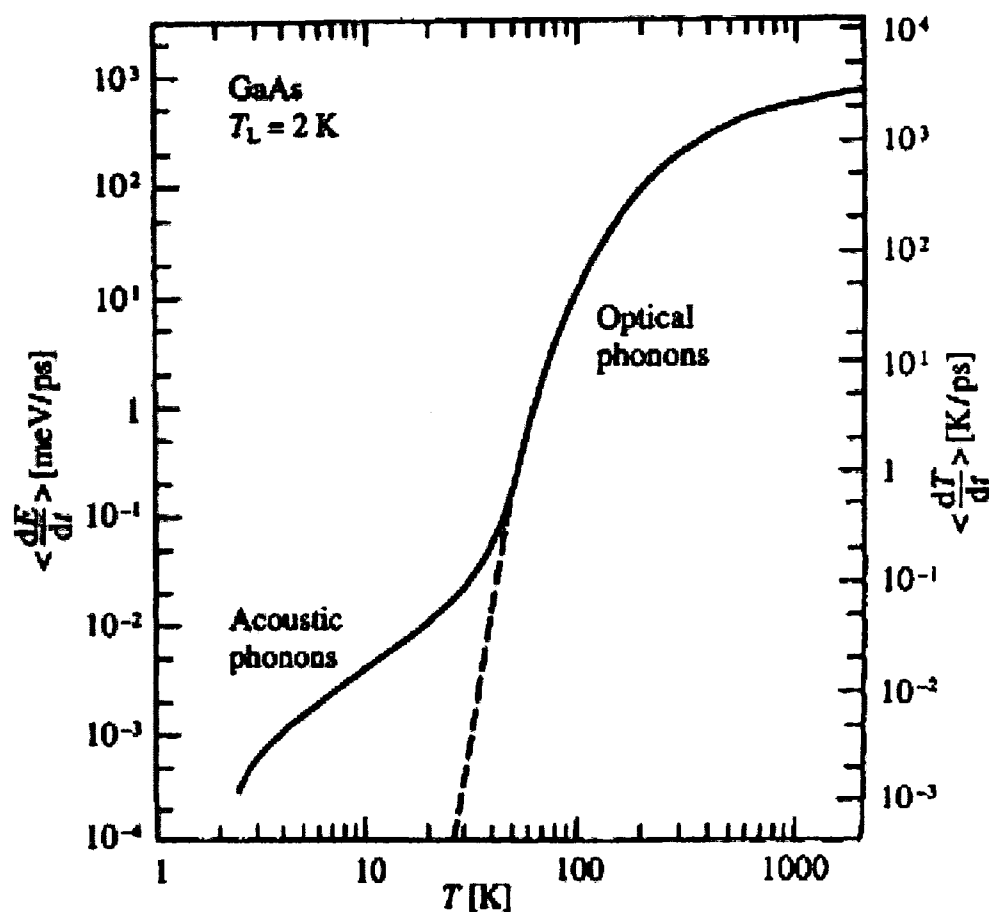


Figure 8.8: Calculated average energy-loss rate per electron-hole pair for a Maxwellian plasma in GaAs at a lattice temperature of 4 K [Shah 1984]. At low carrier temperatures (< 40 K) holes scattering with acoustic phonons dominate the energy loss rate. At higher temperatures the energy loss is mainly due electron-optical phonon interaction. The dashed curve is the optical phonon contribution at low temperatures.

at low lattice and carrier temperatures the ELR is small and determined by the deformation potential and piezoelectric interaction with acoustic phonons.

At slightly higher powers hot carriers enter the SQW and contribute to an increase in temperature. However, the 1D system is always hotter than the 2D system. Interestingly, as the conduction in the SQW increases, the temperature gain in the QWR slows down. As the power is increased further the opposite happens: the temperature increase for carriers in the QWR becomes stronger and the increase in the SQW is reduced. This can be observed

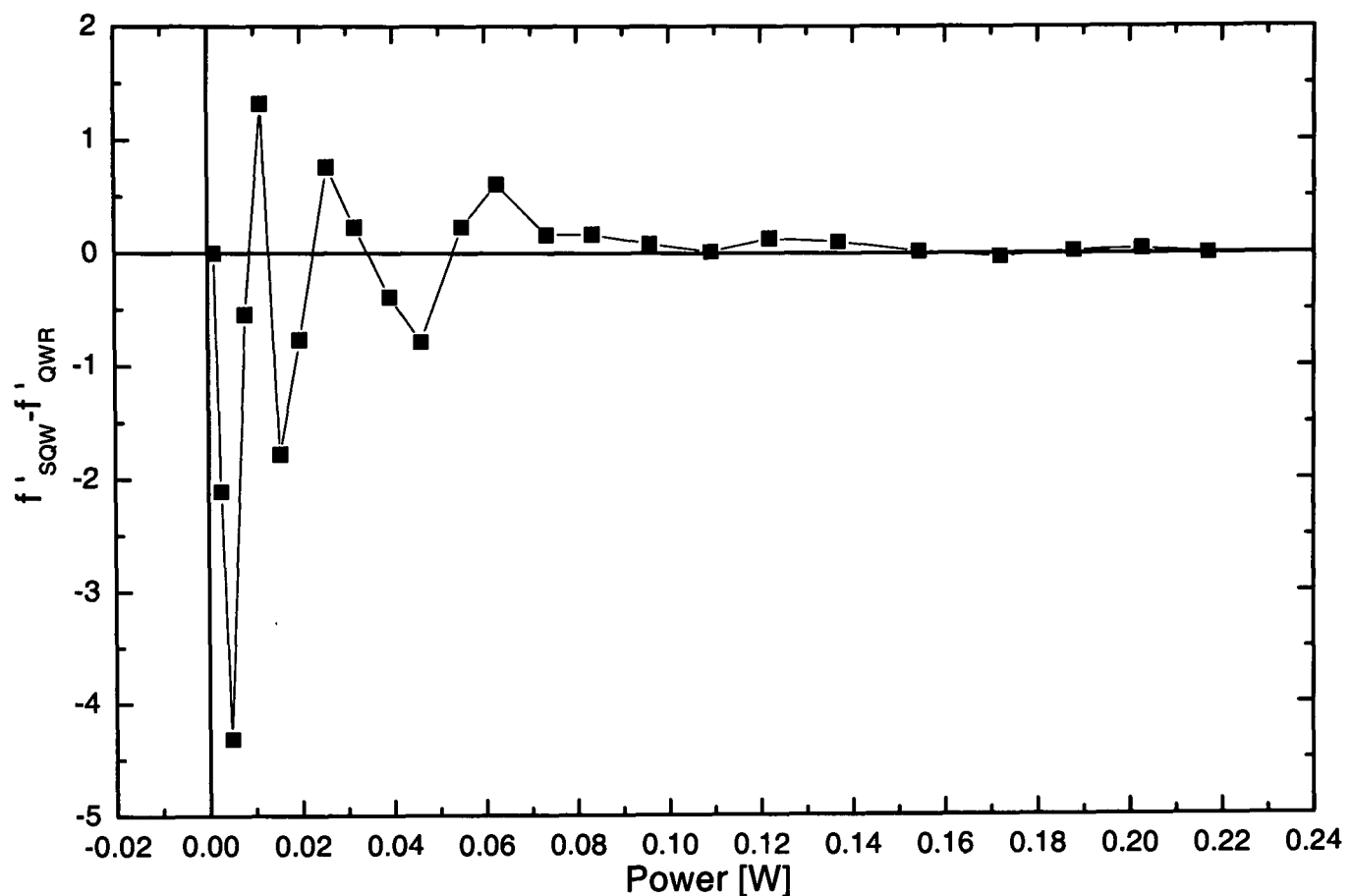


Figure 8.9: *Difference in temperature increase in side quantum well (SQW) and quantum wire (QWR) (sample A2).* To visualize the alternating increase in temperature in the SQW and QWR, the curves for sample A2 in figure 8.7 were differentiated and subsequently subtracted from each other. The resulting curve shows an oscillatory behaviour with strongly decreasing amplitudes indicating an equilibrium between the SQW and QWR carriers.

repeatedly as the voltage is increased. To analyse this phenomenon further both curves were differentiated and subtracted from each other in order to extract the difference in temperature increase between the carriers in the QWR and the SQW. The result, shown in figure 8.9, demonstrates a strongly systematic interaction between QWR and SQW. The curve exhibits an oscillatory behaviour with decaying amplitudes and increasing periods. The decrease in amplitudes indicates an convergence of the carrier temperatures in SQW and QWR towards

a thermal equilibrium. To obtain more quantitative conclusions a theoretical model is needed, which considers factors such as mobilities, tunnelling through the pinch-off potential barrier and thermo-ionic emission, similar to the model used by Hess et al. [1979] for real space transfer (see below).

At temperatures above 30 K the ELR in both the 1D and 2D system increases significantly, as expected for relaxation by LO phonons (fig. 8.8), and increased power dissipation at higher applied fields leads to heating of the lattice. The role of the LO phonon at higher temperatures can be seen clearer for sample B2 (fig. 8.7). Above 50 K the ELR is strongly increased and the slope can be approximated by $(\hbar\omega_{LO}/k) = 427$ K, where $\hbar\omega_{LO} = 36.8$ meV, the LO phonon energy. In fig. 8.7 this slope is fitted to the B3 data and an ELR of

$$\left\langle \frac{dE}{dt} \right\rangle = 18.23 e^{-\frac{\hbar\omega_{LO}}{kT_c}} \quad (8.9)$$

can be calculated, if it is assumed, that the n^{++} -GaAs capping layer in the sample does not contribute to the conduction and that all current flows through the QWR.

Despite the reasonable fit of the ELR with the LO phonon energy a few factors, which can modify the ELR should be included in a refined modelling of the obtained results.

- The model within which the average ELR (8.8) was derived assumes that the carrier density is low enough that the DFs can be described by the Maxwell-Boltzmann function. In highly doped systems the correct DF which has to be used is the Fermi-Dirac function. With this replacement an analytical solution is not possible and numerical tools would have to be employed. However, the degeneracy effect in 3D and 2D was found to be rather small at moderate densities ($1 \times 10^{10} \text{ cm}^{-3}$ and $1 \times 10^{12} \text{ cm}^{-2}$) [Das Sarma 1992].
- Non-equilibrium phonons may lead to a reabsorption of phonons by carrier and hence reduce the net ELR to the lattice [van Driel 1979, Collet 1982, Poetz 1983]. This is particularly the case in highly photoexcited systems or high electric fields. In fact

Shah et al. [1985] have found in modulation-doped quantum wells, that the electron ELR is 25 times smaller than that for holes, instead of the calculated factor of 2.5 due to hot-phonon effects; as the phase space available to holes is larger than for electrons, the hot phonon effect is much smaller for holes than electrons.

- Finally, a large density of photoexcited or background carriers can introduce screening and other many-body effects, like the collective modes of the electronic system (plasmons), plasmon-phonon coupled modes and dynamical screening. These factors can be taken into account by considering the frequency and wavevector-dependent dielectric function $\epsilon(q, \omega)$ [Shah 1998].

8.4 CONCLUSIONS AND OUTLOOK

Several aspects of hot carriers in modulation-doped v-groove QWRs have been investigated:

- Time-resolved measurements have revealed that in v-groove QWR samples with strong pinch-offs between the QWR and the SQW can lead to carrier separation by an inhibited electron capture and to a subsequent reduced recombination rate in the QWR.
- The combined effects of carrier separation due to the pinch-off and the electron trapping at positively charged donor ions could lead to unusually long QWR luminescence lifetimes.
- In a high carrier density QWR sample B2 the lifetime of excited electrons in higher subbands are prolonged due to cooling of a thermalised electron-hole system.
- When a low voltage is applied along the wires, the transport occurs first in the QWR. Only with increasing voltage transport in the 2D channel can be observed. This represents strong evidence for real-space transfer. However, a theoretical model is needed to explain the interaction between the QWR and SQW carriers.

- While at low voltages the ELR is determined by scattering with acoustic phonons, above 30-50 K scattering with LO phonons clearly dominates energy relaxation processes.

APPENDIX: SAMPLE DESCRIPTIONS

The layer sequence and thicknesses of the investigated samples are listed below. Unless otherwise noted Al₃₀Ga₇₀As was grown with a TMAI source (refer to chapter 3).

Sample A1

Thickness	Material	Layers
17 nm	GaAs	Capping
50 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
10 nm	Al ₃₀ Ga ₇₀ As	Doping (DMEAAI)
30 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
2.8 nm	GaAs	Channel
30 nm	Al ₃₀ Ga ₇₀ As	Spacer
10 nm	Al ₃₀ Ga ₇₀ As	Doping
250 nm	Al ₃₀ Ga ₇₀ As	Buffer
50 nm	Al ₃₀ Ga ₇₀ As	Buffer
	GaAs	Substrate

Sample A2

Thickness	Material	Layers
17 nm	GaAs	Capping
50 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
10 nm	Si:Al ₃₀ Ga ₇₀ As 2×10 ¹⁷ cm ⁻³	Doping (DMEAAI)
30 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
2.8 nm	GaAs	Channel

30 nm	Al ₃₀ Ga ₇₀ As	Spacer
10 nm	Si:Al ₃₀ Ga ₇₀ As 1×10 ¹⁷ cm ⁻³	Doping
250 nm	Al ₃₀ Ga ₇₀ As	Buffer
50 nm	Al ₃₀ Ga ₇₀ As	Buffer
	GaAs	Substrate

Sample B1

Thickness	Material	Layers
40 nm	Si:GaAs 4 × 10 ¹⁸ cm ⁻³	Highly doped
20 nm	In _{48.5} Ga _{52.5} P	Contact
20 nm	GaAs	Capping
50 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAl)
10 nm	Al ₃₀ Ga ₇₀ As	Doping (DMEAl)
30 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAl)
3 nm	GaAs	Channel
30 nm	Al ₃₀ Ga ₇₀ As	Spacer
10 nm	Al ₃₀ Ga ₇₀ As	Doping
250 nm	Al ₃₀ Ga ₇₀ As	Buffer
	GaAs	Substrate

Sample B2

Thickness	Material	Layers
40 nm	Si:GaAs 4 × 10 ¹⁸ cm ⁻³	Highly doped
20 nm	In _{48.5} Ga _{52.5} P	Contact
20 nm	GaAs	Capping
50 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAl)
10 nm	Al ₃₀ Ga ₇₀ As 2×10 ¹⁶ cm ⁻³	Doping (DMEAl)
30 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAl)
3 nm	GaAs	Channel
30 nm	Al ₃₀ Ga ₇₀ As	Spacer
10 nm	Al ₃₀ Ga ₇₀ As 1×10 ¹⁶ cm ⁻³	Doping
250 nm	Al ₃₀ Ga ₇₀ As	Buffer
	GaAs	Substrate

Sample B3

Thickness	Material	Layers
40 nm	Si:GaAs $4 \times 10^{18} \text{ cm}^{-3}$	Highly doped
20 nm	In _{48.5} Ga _{52.5} P	Contact
20 nm	GaAs	Capping
50 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
10 nm	Al ₃₀ Ga ₇₀ As $1 \times 10^{17} \text{ cm}^{-3}$	Doping (DMEAAI)
30 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
3 nm	GaAs	Channel
30 nm	Al ₃₀ Ga ₇₀ As	Spacer
10 nm	Al ₃₀ Ga ₇₀ As $5 \times 10^{16} \text{ cm}^{-3}$	Doping
250 nm	Al ₃₀ Ga ₇₀ As	Buffer
	GaAs	Substrate

Sample C & Sample D

Thickness	Material	Layers
5 nm	InGaAs	Contact
15 nm	GaAs	Capping
35 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
3.5 nm	Si: Al ₃₀ Ga ₇₀ As $2 \times 10^{17} \text{ cm}^{-3}$	Doping (DMEAAI)
21 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
10 nm	GaAs	Channel
23 nm	Al ₃₀ Ga ₇₀ As	Spacer
5 nm	Si: Al ₃₀ Ga ₇₀ As $2 \times 10^{17} \text{ cm}^{-3}$	Doping
260 nm	Al ₃₀ Ga ₇₀ As	Buffer
70 nm	Al ₃₀ Ga ₇₀ As	Starting (DMEAAI)
	GaAs	Substrate

Sample E

Thickness	Material	Layers
5 nm	InGaAs	Contact
15 nm	GaAs	Capping
35 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
3.5 nm	Si: Al ₃₀ Ga ₇₀ As $2 \times 10^{17} \text{ cm}^{-3}$	Doping (DMEAAI)

21 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
10 nm	GaAs	Channel
21 nm	Al ₃₀ Ga ₇₀ As	Spacer (DMEAAI)
5 nm	Si: Al ₃₀ Ga ₇₀ As 2×10 ¹⁷ cm ⁻³	Doping (DMEAAI)
315 nm	Al ₃₀ Ga ₇₀ As	Buffer (DMEAAI)
	GaAs	Substrate

BIBLIOGRAPHY

- [Akiyama 1996] H. Akiyama, T. Someya, and H. Sakaki, Phys. Rev. B **53**, R4229 (1996)
- [Altarelli 1986] M. Altarelli, *Semicondcutor Superlattices and Heterojunctions*, Springer Verlag, Berlin, (1986)
- [Ambigapathy 1997] R. Ambigapathy, I. Bar-Joseph, D. Y. Oberli, S. Haacke, M. J. Brasil, F. Reinhardt, E. Kapon, B. Deveaud, Phys. Rev. Lett. **78**, 3579 (1997)
- [Ando 1982] T. Ando, A. B. Fowler, F. Stern, Rev. Mod. Phys. **54**, 437 (1982)
- [Anthony 1994] C. J. Anthony, M. J. Kelly, Semicond. Sci. Tech. **9**, 35 (1994)
- [Bastard 1986] G. Bastard, *Wave Mechanics applied to semiconductor heterostructures* (Springer Verlag, Berlin) 1986
- [Bauer 1992] G. E. W. Bauer, Sakaki, Surf. Sci. **267**, 422 (1992)
- [Biasiol 1996] G. Biasiol, F. Reinhardt, A. Gustafsson, E. Martinet, E. Kapon, Appl. Phys. Lett. **69**, 18 (1996)
- [Biasiol 1997a] G. Biasiol, F. Reinhardt, A. Gustafsson, E. Kapon, Appl. Phys. Lett. **71**, 13 (1997)

- [Biasiol 1997b] G. Biasiol, E. Martinet, F. Reinhardt, A. Gustafsson, E. Kapon, J. of Cryst. Growth **124**, 513 (1997)
- [Biasiol 1998] G. Biasiol, E. Kapon, Phys. Rev. Lett. **81**, 2962 (1998)
- [Bloch 1994] J. Bloch, U. Bockelmann, F. Laruelle, Europhys. Lett. **28** 501(1994)
- [Bockelmann 1991] U. Bockelmann, G. Bastard, Europhys. Lett. **15**, 215 (1991)
- [Brum 1988] J. A. Brum, G. Bastard, Superlatt. Microstruct. **4**, 443 (1988)
- [Calleja 1991] J. M. Calleja, A. R. Goni, B. S. Denni, J. S. Weiner, A. Pinczuk, S. Schmitt-Rink, L. N. Pfeiffer, K. W. West, J. F. Müller, A. E. Ruckenstein, Solid State Com. **79**, 911 (1991)
- [Chang 1985] Y.-C. Chang, L. L. Chang, and L. Esaki, Appl. Phys. Lett. **47**, 1324 (1985).
- [Chaves 1986] A. S. Chaves, A. F. S. Penna, J. M. Worlock, Surf. Sci. **170**, 618 (1986)
- [Chen 1990] W. Chen, M. Fritze, A. V. Murmikko, D. Ackley, C. Colvard, H. Lee, Phys. Rev. Lett. **64**, 2434 (1990)
- [Cho 1987] H. S. Cho, P. R. Prucnal, Phys. Rev. B **36**, 3237 (1987)
- [Christen 1992] J. Christen, E. Kapon, E. Colas, D. M. Hwang, L. M. Schiavone, M. Grundmann, D. Bimberg, Surf. Sci. **267**, 257 (1992)
- [Cingolani 1991] R. Cingolani, H. Lage, H. Kalt, L. Tapfer, D. Heitmann, and K. Ploog, Phys. Rev. Lett. **67**, 891 (1991)
- [Cingolani 1993] R. Cingolani, R. Rinaldi, La Rivista del Nuovo Cimento della Societa Italiana di Fisica **16**, (1993)
- [Citrin 1989] D. S. Citrin, Y.-C. Chang, Phys. Rev. B **40**, 5507 (1989)

- [Citrin 1991] D. S. Citrin, Y.-C. Chang, Phys. Rev. B **43**, 11703 (1991)
- [Collet 1982] J. H. Collet, T. Amand, M. Pugnet, Physics Letters **96A**, 368 (1994)
- [Conwell 1967] E. M. Conwell, *High field transport in semiconductors*, New York, Academic Press (1967)
- [Das Sarma 1992] S. Das Sarma, in *Hot carriers in semiconductor nanostructures: physics and applications*, p. 53, ed. J. Shah, Boston, Academic Press
- [Das Sarma 1994] S. Das Sarma et al., Phys. Rev. B, **49**, 1867 (1994)
- [Delalande 1986] C. Delalande, J. Organasi, M. H. Meynadier, J. A. Brum, G. Bastard, G. Weimann, W. Schlapp, Solid St. Commun. **59**, 613 (1986)
- [Demtröder 1996] W. Demtröder, *Laser Spectroscopy*, Springer-Verlag, second edition (1996)
- [Dieker 1999] Ch. Dieker, DGE Conference, Proceedings (1999)
- [Dingle 1980] R. Dingle, H. L. Störmer, A. C. Gossard, W. Wiegmann, Appl. Phys. Lett. **33**, 665 (1978)
- [Esaki 1970] L. Esaki, R. Tsu, IBM Res. Develop. page 61 (1970)
- [Friedel 1969] J. Friedel, Comments Solid State Phys. **2**, 21 (1969)
- [Fritze1993] M. Fritze, A.V. Nurmikko and P. Hawrylak, Phys. Rev. B **48**, 4960 (1993)
- [Fröhlich 1937] H. Fröhlich, Proc. Roy. Soc. **160**, 230 (1937)
- [Gershoni 1990] D. Gershoni, J. S. Weiner, S. N. G. Chu, G. A. Baraff, J. M. Vandenberg, L. N. Pfeiffer, K. W. West, R. A. Logan, T. Tanbum, Phys. Rev. Lett. **65**, 1631 (1990).

- [Goni 1992] A. R. Goni, L. N. Pfeiffer, K. W. West, A. Pinczuk, H. U. Baranger, and H.L. Störmer, Appl. Phys. Lett. **61**, 1956 (1992)
- [Gustafsson 1995] A. Gustafsson, F. Reinhardt, G. Biasiol, E. Kapon, Appl. Phys. Lett. **67**, 25 1995
- [Hammersberg 1996] J. Hammersberg, H. Wehman, N. Notomi, T. Lundstrom, T. Tanamura and M. Potemski, Phys. Rev. B **54**, 4835 (1996)
- [Hardtdegen 1994a] H. Hardtdegen, Chr. Ungermanns, M. Hollfelder, T. Raafat, R. Carius, S. Haselöhr, Hans Lüth, J. Cryst. Growth **145**, 478 (1994)
- [Hardtdegen 1994b] H. Hardtdegen, M. Hollfelder, Chr. Ungermanns, T. Raafat, R. Carius, A. Förster, J. Lange, and Hans Lüth, Inst. Phys. Conf. Ser. 141, Chap. 2, page 81, (1994)
- [Hauert 2000] M. Hauert, *Near-field spectroscopy of semiconductor nanostructures*, DPhil thesis Clarendon Laboratory, Oxford University (2000)
- [Hawrylak 1992] P. Hawrylak, Solid State Com. 81525 (1992)
- [Hess 1979] K. Hess, H. Morkoc, H. Shicijo, B. G. Streetman, Appl. Phys. Lett. **35**, 469 (1979)
- [Hess 1998] K. Hess, *Milestones of hot-electron research in Hot electrons in semiconductors*, ed. N. Balkan, Oxford University Press (1998)
- [Hu 1992] B. Hu and S. Das Sarma, Phys. Rev. Lett. **68**, 1750 (1992)
- [Illing 1995] M. Illing, G. Bacher, T. Kümmel, A. Forchel, T. G. Andersson, D. Hommel, B. Jobst, and G. Landwehr, Appl. Phys. Lett. **67**, 124 (1995)
- [Kajikawa 1993] Y. Kajikawa, Phys. Rev. B **47**, 3649 (1993), and references therein

- [Kaluza 2000] A. Kaluza Ph.D. thesis 2000, RWTH Aachen, Germany
- [Kane 1957] E. O. Kane, J. Phys. Chem. Solids **1**, 249 (1957)
- [Kapon 1987] E. Kapon, M. C. Tamargo, D. M. Huang, Appl. Phys. Lett. **50**, 347 (1987)
- [Kapon 1989] E. Kapon, D. M. Huang, R. Bhat, Phys. Rev. Lett. **63**, 430 (1989)
- [Kapon 1992] E. Kapon, K. Kash, E. M. Clausen, Jr. D. M. Hwang, and E. Colas, Appl. Phys. Lett. **60**, 477 (1992)
- [Kash 1991] J. A. Kash, J. C. Tsang, *Light scattering in Solids VI*, Eds. M. Cardona, G. Guntherodt, Springer Verlag, Berlin, p. 423 (1991)
- [Kiener 1995] C. Kiener, L. Rota, J. M. Freyland, K. Turner, A. C. Maciel, J. F. Ryan, U. Marti, D. Martin, F. Morier-Gemoud, F. K. Reinhart, Appl. Phys. Lett. **67**, 2851 (1995)
- [Kiener 1996a] C. Kiener, L. Rota, K. Turner, J. M. Freyland, A. C. Maciel, J. F. Ryan, U. Marti, D. Martin, F. Morier Gemoud, F. K. Reinhart, Solid State Elec. **40**, 257 (1996)
- [Kiener 1996b] C. Kiener, L. Rota, A. C. Maciel, J. M. Freyland, J. F. Ryan, Appl. Phys. Lett. **68**, 2061 (1996)
- [Kim 1999] J. Kim, A. C. Maciel, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, Th. Schäpers, H. Lüth, D. Meertens, Ch. Dieker, Physica E **7**, 517 (2000)
- [Kohl 1990] M. Kohl, D. Heitmann, W. W. Ruhle, P. Grambow, and K. Ploog, *Proceedings of the 20th International Conference on Physics Semiconductors*, edited by E. M. Anastaskais and J. D. Joannopoulos (World Scientific, Singapore, 1990), p. 2399

- [Komori 1996] K. Komori, X.-L. Wang, M. Ogura, H. Matsuhata, H. Imanishi, *Appl. Phys. Lett.* **68**, 26 (1996)
- [Kümmell 1998] T. Kümmell, G. Bacher, A. Forchel, G. Lermann, W. Kiefer, B. Jobst, D. Hommel, and G. Landwehr, *Phys. Rev. B* **57**, 15439 (1998).
- [Landau 1977] L. D. Landau, E. M. Lifshitz, *Quantum Mechanics*, Pergamon Oxford, 3rd edition, p. 73 (1977)
- [Lomascolo 1998] M. Lomascolo, P. Ciccarese, R. Cingolani, R. Rinaldi, F. K. Reinhart, J. *Appl. Phys.* **83**, 1 (1998)
- [Luttinger 1955] J. M. Luttinger, W. Kohn, *Phys. Rev.* **97**, 869 (1955)
- [Maciel 1994] A. C. Maciel, J. F. Ryan, R. Rinaldi, R. Cingolani, M. Ferrara, U. Marti, D. Martin, F. Morier-Gemoud, and F. K. Reinhart, *Semicond. Sci. Technol.* **9**, 893 (1994)
- [Maciel 1995] A. C. Maciel, C. Kiener, L. Rota, J. F. Ryan, U. Marti, D. Martin, F. Morier Gemoud, F. K. Reinhart, *Appl. Phys. Lett.* **66**, 3039 (1995)
- [Maciel 1999] A. C. Maciel, J. Kim, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, Th. Schäpers, D. Meertens, Ch. Dieker, H. Lüth, *Physica B* **272**, 101, (1999)
- [Maciel 2000] A. C. Maciel, J. Kim, H. D. M. Davies, E. D. O'Sullivan, J. F. Ryan, A. Schwarz, A. Kaluza, H. Hardtdegen, Th. Schäpers, D. Meertens, Ch. Dieker, H. Lüth, *Physica E* **6**, 530 (2000)
- [Mahan 1967] G. D. Mahan, *Phys. Rev.* **153**, 882 (1967), G. D. Mahan, *Phys. Rev.* **163**, 612 (1967)

- [Mahan 1990] G. Mahan, *Many Particle Physics* (Plenum, New York, 1990).
- [Martinet 1997] E. Martinet, A. Gustafsson, G. Biasiol, F. Reinhardt, E. Kapon, *Phys. Rev. B* **56**R5796 (1997)
- [Martinet 1998] E. Martinet, F. Reinhardt, A. Gustafsson, G. Biasiol, E. Kapon, *Appl. Phys. Lett.* **72**, 6 (1998)
- [Mayer 1990] G. Mayer, B. E. Maile, R. Germann, A. Forchel, P. Grambow, and H. P. Meier, *Appl. Phys. Lett.* **56**, 2016 (1990)
- [Menschig 1990] A. Menschig, A. Forchel, B. Roos, R. Germann, K. Pressel, W. Heuring, D. Grutzmacher, *Appl. Phys. Lett.* **57**, 1757 (1990)
- [Motohisa 1992] J. Motohisa and H. Sakaki, *Appl. Phys. Lett.* **60**, 1315 (1992)
- [Müller 1990] J.F. Müller, *Phys. Rev. B* **42**, 11189 (1990)
- [Müller 1992] J. F. Müller, A. E. Ruckenstein, S. S. Schmitt-Rink, *Mod. Phys. Rev. B* **45**, 8902(1992)
- [Nag 1980] B. R. Nag, *Electron transport in compound semiconductors*, Berlin Springer Verlag (1980)
- [Nagamune 1992] Y. Nagamune, Y. Arakawa, S. Tsukamoto, M. Nishioka, *Phys. Rev. Lett.* **69**, 2963 (1992)
- [Nozieres 1969] P. Nozieres and C. T. de Dominicis, *Phys. Rev.* **178**, 1097 (1969).
- [Numerical Algorithm Group 1983] *The NAG Fortran PC50 Library Handbook*, 1st edition 169 (1983)

- [O'Sullivan 2000] E. O'Sullivan, DPhil thesis, Clarendon Laboratory, Oxford University (2000)
- [Oberli 1999] D. Y. Oberli, M.-A. Dupertuis, F. Reinhart, E. Kapon, Phys. Rev. B **59**, 2910 (1999)
- [Ogawa 1991] Testuo Ogawa and Toshihide Takagahara, Phys. Rev. B **43**, 14325 (1991); **44**, 8138 (1991)
- [Ogawa 1992] T. Ogawa, A. Furusaki, N. Nagaosa, Phys. Rev. Lett. **68** 3638 (1992)
- [Ohtaka 1989] K. Ohtaka and Y. Tanabe, Phys. Rev. B **39**, 3054 (1989)
- [Ohtaka 1990] K. Ohtaka and Y. Tanabe, Rev. Mod. Phys. **62**, 929 (1990).
- [Okada 1997] H. Okada, H. Fujikura, T. Hashizume, and H. Hasegawa, Jpn. J. Appl. Phys. Part 1 **36**, 1672 (1997).
- [Petroff 1984] P. M. Petroff, A. C. Gossard, R. A. Logan, W. Wiegmann (1982), Appl. Phys. Lett. **45**, 620 (1984)
- [Pfeiffer 1988] L. N. Pfeiffer, K. W. West, H. L. Stormer, J. P. Eisenstein, K. W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 7635 (1988).
- [Pfeiffer 1990] L. Pfeiffer, K. W. West, H. L. Störmer, J. P. Eisenstein, K. W. Baldwin, D. Gershoni, and J. Spector, Appl. Phys. Lett. **56**, 1697 (1990)
- [Pfeiffer 1994] L. Pfeiffer, W. Wegscheider, A. Pinczuk, K. W. West, 7th Int. Conf. Superlattices, *Microstructures and Microdevices*, Banff, Alberta, Canada, Paper S10.1, page 113 in abstract book (1994)
- [Plaut 1991] A.S. Plaut, H. Lage, P. Grambow, D. Heitmann, K. von Klitzing, and K. Ploog, Phys. Rev. Lett. **67**, 1642 (1991)

- [Poetz 1983] W. Poetz, P. Kocevar, Phys. Rev. B **28**, 7040 (1983)
- [Rinaldi 1994a] R. Rinaldi, M. Ferrara, R. Cingolani, U. Marti, D. Martin, F. Morier-Gemoud, P. Ruterana, F. K. Reinhart, Phys. Rev. B **50**, 11795 (1994)
- [Rinaldi 1994b] R. Rinaldi, R. Cingolani, R. Lepore, M. Ferrara, I. M. Catalano, F. Rossi, E. Molinari, P. Lugli, U. Marti, D. Martin, F. Morier-Gemoud, P. Ruterana, F. K. Reinhart, Phys. Rev. Lett. **73**, 2899
- [Rodriguez 1993] F. J. Rodriguez, C. Tejedor, Phys. Rev. B **47** 1506 (1993); **49**, 16781 (1994)
- [Rodriguez 1994a] F. J. Rodriguez, C. Tejedor, Phys. Rev. B **49**, 16781 (1994)
- [Rodriguez 1994b] F.J. Rodriguez, Ph.D. thesis, Universidad Autonoma de Madrid, 1994
- [Roskos 1992] H. G. Roskos, M. C. Nuss, J. Shah, K. Leo, D. A. B. Miller, Phys. Rev. Lett. **68**, 2216 (1992)
- [Rossi 1996a] F. Rossi, E. Molinari, Phys. Rev. Lett. **76**, 3642 (1996)
- [Rossi 1996b] F. Rossi, E. Molinari, Phys. Rev. B **53**, 16462 (1996)
- [Rota 1995] L. Rota, F. Rossi, P. Lugli, E. Molinari, Phys. Rev. B **52**, 5183 (1995)
- [Ruckenstein 1987] A. E. Ruckenstein and S. Schmitt Rink, Phys. Rev. B **35**, 7551 (1987).
- [Ryan 1988] J. F. Ryan, M. Tatham, D. J. Westland, C. T. Foxon, M. D. Scott, W. I. Wang, Proc. SPIE **942**, 256 (1988)
- [Ryan 1996] J. F. Ryan, A. C. Maciel, C. Kiener, L. Rota, K. Turner, J. M. Freyland, U. Marti, D. Martin, F. Morier-Gemoud, F. K. Reinhart, Phys. Rev. B **53**, 4225(1996)

- [Sa'ar 1996] A. Sa'ar, A. Givant, S. Calderon, O. Ben-Shalom, E. Kapon, A. Gustafsson, D. Oberli, C. Caneau, *Superlatt. and Microstr.* **19**, 217 (1996)
- [Sakaki 1980] H. Sakaki, *J. Jpn. Appl. Phys. Part 2* **19**, L735 (1980)
- [Schäpers 1997] Th. Schäpers, A. Hartmann, A. Schwarz, H. Hardtdegen, M. Bongartz, Ch. Dieker and H. Lüth, *App. Surf. Sci.* **123/24** 687 (1997)
- [Schmitt-Rink 1986] S. Schmitt-Rink, C. Ell, and H. Haug, *Phys. Rev. B* **33**, 1183 (1986)
- [Schwarz 1997] A. Schwarz *Magnetotransportmessungen an modulationsdotierten GaAs/Al_{1-x}Ga_xAs Quantendrähten in V-Gräben*, Diplomarbeit, RWTH Aachen, Germany, Sept. 1997
- [Schwarz 1999] A. Schwarz, A. Kaluza, Th. Schäpers, H. Hardtdegen, H. Lüth, D. Meertens, Ch. Dieker, A. C. Maciel, J. Kim, E. D. O'Sullivan, J. F. Ryan, *Physica E* **7**, 760 (2000)
- [Sercel 1990] P. C. Sercel, K. J. Vahala, *Appl. Phys. Lett.* **57**, 545 (1990)
- [Sercel 1991] P. C. Sercel, K. J. Vahala, *Phys. Rev. B* **44**, 5681 (1991)
- [Shah 1969] J. Shah, R. C. C. Leite, J. F. Scott, *Sol. St. Commun.* **8**, 1089 (1969)
- [Shah 1978] J. Shah, *Solid-State Electronics* **21**, 43 (1978)
- [Shah 1983] J. Shah, A. Pinczuk, H. L. Stroemer, A. C. Gossard, W. Wiegmann, *Appl. Phys. Rev.* **42**, 55 (1983)
- [Shah 1984] J. Shah, A. Pinczuk, H. L. Stroemer, A. C. Gossard, W. Wiegmann, *Appl. Phys. Rev.* **44**, 322 (1984)

- [Shah 1985] J. Shah, A. Pinczuk, A. C. Gossard, W. Wiegmann, *Phys. Rev. Lett.* **54**, 2045 (1985)
- [Shah 1992] J. Shah, *Ultrafast Luminescence Studies of Carrier Relaxation and Tunneling in Semiconductor Nanostructures in Hot Carriers in Semiconductors Nanostructures*, AT&T Company (1992)
- [Shah 1998] J. Shah, *Optical spectroscopy as a tool in hot-electron studies in Hot electrons in semiconductors*, ed. N. Balkan, Oxford University Press (1998)
- [Shields 1994] A. J. Shields, C. L. Foden, M. Pepper, D. A. Ritchie, M. P. Grimshaw, G. A. C. Jones, *Superlatt. Microstr.* **15**, 355 (1994)
- [Skolnick 1987] M. S. Skolnick, J. M. Rorison, K. J. Nash, D. J. Mowbray, P. R. Tapster, S. J. Bass, A. D. Pitt, *Phys. Rev. Lett.* **58**, 2130 (1987)
- [Southgate 1971] P. D. Southgate, D. S. Hall, A. B. Dreeben, *J. Appl. Phys.* **42**, 2868 (1971)
- [Steer 1998] M. J. Steer, D. J. Mowbray, M. S. Skolnick, W. R. Tribe, A. N. Forshaw, D. M. Whittaker, J. S. Roberts, A. G. Cullis, G. Hill, M. Pate, C. R. Whitehouse, *Physics E* **7**, 949 (1998)
- [Stern 1984] M. B. Stern, H. G. Craighead, P. F. Liao, P. M. Mankewich, *Appl. Phys. Lett.* **45**, 410 (1984)
- [Störmer] H.L. Störmer unpublished
- [Sweeny 1988] M. Sweeny, J. Xu, M. Shur, *Superlatt. Microstruct.* **4**, 623 (1988)
- [Taguchi 1988] S. Taguchi, T. Goto, M. Takeda, G. Kido, *J. Phys. Soc. Jpn.* **57**, 3256 (1988)
- [Takenaka 1978] N. Tanenaka, M. Inoue, J. Shirafuji, Y. Inuishi, *J. Phys. Soc. Jpn.* **42**, 1630 (1978)

- [Thomas 1996] K. J. Thomas, J. T. Nicholls, M. Y. Simmons, M. Pepper, D.R. Mace, D. A. Ritchie, Phys. Rev. Lett. **77**, 135 (1996)
- [Thornton 1986] T. J. Thornton, M. Pepper, H. Ahmed, D. Andrews, G. J. Davies, Phys. Rev. Lett. **56** 1198 (1986)
- [Tiwari 1994] S. Tiwari, G. D. Pettit, K. R. Milkove, F. Legoues, R. J. Davis, J. M. Woodall, Appl. Phys. Lett. **64**, 3536 (1994)
- [Tribe 1997] W. R. Tribe, M. J. Steer, D. J. Mowbray, D. M. Whittaker, M. S. Skolnick, A. N. Forshaw, J. S. Roberts, G. Hill, M. A. Pate, C. R. Whitehouse, G. M. Williams, Appl. Phys. Lett. **70**, 993 (1997)
- [Tribe 1998] W. R. Tribe, M. J. Steer, A. N. Forshaw, K. L. Schumacher, D. J. Mowbray, D. M. Whittaker, M. S. Skolnick, J. S. Roberts, G. Hill, Appl. Phys. Lett. **73**, 3420 (1998)
- [Tsuchiya 1989] M. Tsuchiya, J. M. Gaines, R. H. Yan, R. J. Simes, P. O. Holtz, L. A. Coldren, and P. M. Petroff, Phys. Rev. Lett. **62**, 466 (1989)
- [Turner 1995] K. Turner, DPhil. thesis, *Hot carrier Relaxation in GaAs Quantum wells and ν -groove quantum wires*, Clarendon Laboratory, Oxford University
- [Uenoyama 1990] T. Uenoyama and L. J. Sham, Phys. Rev. Lett. **65**, 1048 (1990)
- [van der Meulen 1998] H. P. van der Meulen, J. Rubio, I. Azcona, J. M. Calleja, T. C. Rojas, S. I. Molina, R. Garcia, U. Marti, Phys. Rev. B **58**, 10705 (1998)
- [van Driel 1979] H. M. van der Driel, Phys. Rev. B **19**, 5928 (1979)
- [van Houten 1987] H. van Houten, B. J. van-Wees, J. E. Mooij, G. Roos, K. F. Berggren, Superlatt. and Microstr. **497** (1987)

- [Voullioz 1997] F. Voullioz, D. Y. Oberli, M.-A. Dupertuis, A. Gusrafsson, F. Reinhardt, E. Kapon, Phys. Rev. Lett. **78**, 1580 (1997)
- [Voullioz 1998] F. Voullioz, D. Y. Oberli, M.-A. Dupertuis, A. Gustafsson, F. Reinhardt, E. Kapon, Phys. Rev. B **57**, 12378 (1998)
- [Walther 1992] M. Walther, E. Kapon, J. Christen, D. M. Hwang, R. Bhat, Appl. Phys. Lett. **60**, 521 (1992)
- [Wang 1995] X.-L. Wang, M. Ogura, H. Matsuhata, Appl. Phys. Lett. **66**, 1506 (1995)
- [Wang 1997] X.-L. Wang, M. Ogura, H. Matsuhata, A. Hamoudi, Appl. Phys. Lett. **71**, 15, (1997)
- [Wegscheider 1994] W. Wegscheider, L. N. Pferffer, K. West, and R. E. Leibenguth, Appl. Phys. Lett. **65**, 2510 (1994).
- [Weman 1992] H. Weman, M. S. Miller, and J. L. Merz, Phys. Rev. Lett. **68**, 3656 (1992)
- [Yariv 1989] A. Yariv, Quantum Electronics, John Wiley & Sons, third edition (1989)
- [Zener 1934] C. Zener Proc. Roy. Soc. **145**, 523 (1934)

