



HOKKAIDO UNIVERSITY

Title	Terahertz Cyclotron Resonance in III-V Quantum Hall Systems
Author(s)	DICKSON ZAKARIA KINDOLE
Degree Grantor	北海道大学
Degree Name	博士(理学)
Dissertation Number	甲第13906号
Issue Date	2020-03-25
DOI	https://doi.org/10.14943/doctoral.k13906
Doc URL	https://hdl.handle.net/2115/94525
Type	doctoral thesis
File Information	DICKSON_ZAKARIA_KINDOLE.pdf



Doctoral Dissertation

**Terahertz Cyclotron Resonance in
III-V Quantum Hall Systems**

(テラヘルツサイクロトロン共鳴による III-V 族半導体量子ホール系に関する研究)

Dickson Zakaria Kindole

Graduate School of Science, Hokkaido University

Department of Condensed Matter Physics

2020 March

Abstract

Semiconductor two-dimensional electron system is one of the promising materials for the study of fundamental physics and for exploring of phenomena such as integer and fractional quantum Hall effect. Detailed study of electronic properties in these systems are important for fundamental research and device application.

In this dissertation, cyclotron resonance (CR) experiments were studied in the terahertz range for the GaN, InGa_N and InGaAs two-dimensional electron systems using a Fourier transform spectrometer in combination with a high-field superconducting magnet.

High quality samples of GaN and InGa_N heterostructures were grown on sapphire substrates using metal-organic chemical vapor deposition, and those of InGaAs with inverted heterostructures were grown on GaAs substrate by the molecular beam epitaxy technique. The quality of the samples were investigated by the magneto-transport measurements, and the Shubnikov-de Haas oscillation and quantum Hall plateaus were observed, indicating that the samples have enough mobility for carrying out the CR experiments.

In the CR results of GaN two-dimensional electron system (2DES), non-linear dependence of the CR energy against magnetic field was observed. This indicates that the effective mass becomes heavier with increasing magnetic fields. The mass enhancement from the bare mass of GaN was investigated in detail from the view point of both the band non-parabolicity and polaron effect. It is concluded that the effective mass of the 2DES is strongly affected by the carrier density and electron-phonon interaction. Consequently, the contradiction in relation to the widely reported effective mass of GaN 2DES have been clarified in the present work.

The CR absorption was observed even in InGa_N 2DES at each magnetic field. This is the first observation of the CR, and determination of the effective mass in InGa_N 2DES. The effective mass was found to decrease gradually with increasing indium concentration. Such a tendency is possible to describe by using Vegard's law with the introduction of bowing term in the linear equation. The effective mass was explained perfectly for the entire indium concentration.

In the case of CR results of InGaAs inverted heterostructures, several anomalous phenomena (CR splitting, drastically change of the effective mass and anti-crossing of the CR line in the vicinity of transverse-optical phonon energy) were observed. These phenomena were discussed based on Rashba effect and magneto plasmon-phonon mixing effect for the high carrier density systems.

In summary, the CR experiments have been performed in the terahertz range in GaN, InGa_N and InGaAs 2DES. Through the CR measurements, fundamental material parameters such as the effective mass have been studied. A variety of phenomena in relation to band non-parabolicity, electron-phonon interaction, Rashba type spin-orbit interaction and magneto plasmon-phonon mixing mode have been explored, and their influence to electronic properties of the 2DES have been understood.

Table of Contents

Introduction	1
1.1 Research Background	1
1.2 Purpose and outline.....	3
Theoretical Background	6
2.1 III-V compound semiconductors	6
2.1.1 Band structure of wurtzite crystal	7
2.1.2 Band structure of zinc blend crystal	10
2.1.3 Ternary alloys.....	11
2.2 Effective mass in semiconductor.....	12
2.3 Quantum structures.....	15
2.3.1 Growth of semiconductor multilayers	15
2.3.2 Two-dimensional semiconductors	17
2.4. Classical Drude model	21
2.5 Electron motion in magnetic fields.....	23
2.5.1 Landau levels	23
2.5.2 Cyclotron resonance	27
2.5.3 Cyclotron resonance in 2DES.....	29
2.5.4 Cyclotron resonance absorption.....	31
2.6 Magneto-transport phenomena.....	33
2.6.1 Hall effect in semiconductors.....	33
2.6.2 Quantum Hall effect	35
2.6.3 Shubnikov-de Hass oscillation.....	36
2.7 Band non-parabolicity.....	37
2.8 Polaron effect.....	39
2.9 Rashba effect	43
2.10 Plasmon	47
Samples and Experiments.....	50
3.1 Growth techniques.....	50
3.1.1 AlGa _N /InGa _N and AlGa _N /Ga _N heterostructures	53
3.1.2 InGaAs/InAlAs heterostructures	55
3.2 Magneto-transport measurements.....	56
3.3 Cyclotron resonance measurements	62
3.3.1 Sample preparation for CR measurements	63
3.3.2 Fourier transform spectrometer.....	65
3.3.3 Bolometer.....	67

3.3.4 CR experiments	69
3.3.5 CR spectra	70
AlGa_N/Ga_N Heterostructures	71
4.1 Introductory statement	71
4.2 Magneto-transport results.....	72
4.3 CR results and discussion.....	74
4.3.1 Band non-parabolic effect.....	77
4.3.2 Polaron effect	80
4.3.3 Electron mobility.....	85
4.4 Conclusions	86
AlGa_N/InGa_N Heterostructures.....	87
5.1 Introductory statement	87
5.2 Magneto-transport results.....	87
5.3 CR results and discussion.....	89
5.4 Temperature dependence of SdH oscillation.....	96
5.4.1 SdH Oscillation mass.....	96
5.4.2 Scattering mechanism.....	100
5.5 Conclusions	101
InGaAs/InAlAs Heterostructures	103
6.1 Introductory statement	103
6.2 Magneto-transport results.....	103
6.3 CR results and discussion.....	104
6.4 Conclusions	110
Summary	111
7.1 Conclusions	111
7.2 Future works.....	112
References	113
Journal Publications, Conferences, Symposiums, Meetings and Seminars	121
List of Journal Publications	121
List of International Conferences and Symposiums.....	121
List of Domestic conferences, Symposiums, Meetings and Seminars	122
Acknowledgement.....	124

CHAPTER ONE

Introduction

1.1 Research Background

Two-dimensional electron system (2DES) was originally realized in silicon metal oxide-semiconductor field-effect transistor (Si-MOSFET) since the 1960s. In two-dimensional semiconductor, the carriers are located and confined in a triangular potential formed at the interface (i.e. between silicon and silicon oxide, in case of Si-MOSFET). Although the motion perpendicular to the interface (z -direction) is confined, the electrons can freely move (in x and y -directions) at the heterointerface. Since their discovery, the transport properties of 2DES has received considerable attention. Thus, in 1980s, the quantum Hall effect (QHE) which is the epoch-making phenomenon observed in 2DES subjected to low temperatures and high magnetic fields, was firstly discovered by Professor von Klitzing from the Si-MOSFET. Hard to the heels of the discovery of QHE leads to the observation of fractional QHE in a very high-quality GaAs heterojunction in 1982s [1-4].

The progress of epitaxial growth technology in the recent years, has made possible to realize high quality 2DES in various semiconductors. In particular, several kinds of semiconductor heterostructures have been engineered from both molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) techniques enabling to study QHE. Figure 1.1 shows a typical fractional QHE in MgZnO/ZnO 2DES. The Shubnikov-de Haas oscillation and fractional quantum Hall plateaus were clearly observed, indicating that a very high-quality sample can be realized even in the wide-bandgap semiconductors. Consequently, strong electron correlation effects which is difficult to access in other semiconductors, can be studied in ZnO [5].

Nowadays, even heterostructures from wide bandgap energy, narrow bandgap and alloyed semiconductors such as GaN, InGaN and InGaAs have been utilized for growing 2DES. While in InGaAs heterostructures, doping technique is a key to realize high mobility 2DES, heterostructures of

GaN and InGaN have the ability to form 2DES without intentional doping technique. They can create the 2DES at the heterointerface through intrinsic spontaneous and piezoelectric polarization. Semiconductor heterostructures with high electron mobilities are not only important for exploring special phenomena which have the possibility to open up a new research window, but also for future device application. Not only integer and fractional Quantum Hall effect but also high-speed switching and high operation frequencies are the highlights of the 2DES. Thus, high-mobility 2DES in various heterostructures provides a special system to investigate electron properties of semiconductors [5, 6].

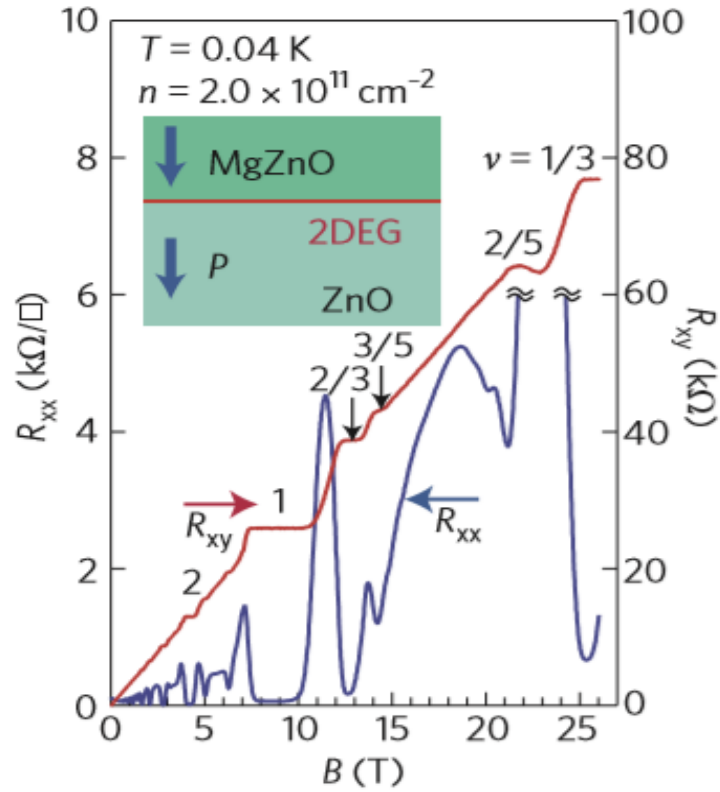


Figure 1.1 FQHE in MgZnO/ZnO 2DES. The Shubnikov-de Haas oscillation and fractional quantum Hall plateaus are observed, indicating high electron mobility even in wide-gap semiconductor [5].

GaN, InGaN and InGaAs have attracted considerable attention for not only fundamental physics but also for its potential application to various electronic devices. GaN-based power-electronic devices,

for example, is capable of delivering higher breakdown voltage than Si-based devices because of its wide bandgap energy (3.5 eV at room temperature) [7]. InGaN is also a very attractive material for future photovoltaic devices. This is because the bandgap energy can be varied continuously from 0.7 eV (InN) to 3.5 eV (GaN), providing a full-solar-spectrum for multijunction solar cells [7, 8]. Furthermore, InGaAs has the potential for realizing novel spintronic devices because of the larger spin-orbit interaction among narrower-gap semiconductors [9-11].

However, fundamental studies of the band parameters such as the effective mass of carriers and their dependencies on the carrier density and indium concentration of these semiconductors are not adequate. For example, the effective mass of the two-dimensional electron system of GaN was reported widely between 0.18 and 0.27 m_0 [12-14], so far. Such a large variation of the effective mass of GaN is incomprehensive, hence, the origin and the reason responsible for the effect should be found. In particular, detailed electronic properties related to InGaN 2D systems have not been reported yet because it is difficult to obtain a high-quality InGaN film. This is mainly due to lack of suitable substrates and growth temperature optimization [15]. For InGaAs, the spin-splitting energy (Rashba effect) and effective mass were studied through the beat pattern analysis or the fast Fourier transform analysis in the Shubnikov-de Haas (SdH) oscillation [10,11]. Cyclotron resonance is also a powerful tool for the direct observation of the effective mass and spin splitting energy. In addition, the application of high magnetic field can rise exploration of special phenomenon in relation to electron phonon interaction, band non-parabolicity and Rashba effect. Accurate band parameters and detailed understanding of electronic properties of these materials are quite important for fundamental research and device application.

1.2 Purpose and outline

The main purpose of this dissertation is to carry out cyclotron resonance experiments in

AlGa_N/Ga_N, AlGa_N/InGa_N and InGaAs/InAlAs heterostructures in order to investigate material parameters such as the effective mass, carrier concentration and mobility. Moreover, this work aims to explore special phenomena related to electron-phonon interaction, band non-parabolicity and spin-orbit interaction at high magnetic field regime.

This dissertation consists of seven chapters, and the outline is briefly described as follows. In chapter one the background and the purpose of this study are presented. Chapter two contains theoretical background of some important topics of interest which include; III-V semiconductors, Quantum structures, Landau levels and cyclotron resonance are presented in-line with the related special phenomena such as polaron effect, band non-parabolicity and Rashba effect. In addition, overview of magneto-transport phenomena (Shubnikov-de Haas oscillation and quantum Hall effect) is presented here as they are important for understanding the sample quality in terms of mobilities as a prerequisite for carryout cyclotron resonance experiments.

Chapter three provides an overview on the growth techniques, sample details, measurement techniques, and experimental set up for cyclotron resonance and magneto-transport measurements. Although, detailed growing process of the samples are beyond the scope of this dissertation, this chapter highlights some specific epitaxial growth technique used for growth of high-quality samples. Various experimental equipment and instruments that were used to conduct experiments are presented. In addition, the results of magnet-transport measurements will be given in this chapter.

Chapter four provides the results and discussion of AlGa_N/Ga_N heterostructures for three samples having different carrier concentrations. Non-linear dependence of the cyclotron energy against magnetic field was observed. In particular, the electron effective mass enhancement from the bulk value is discussed from view point of both the polaron effect and the band non-parabolicity.

In chapter five, the results of cyclotron resonance measurements in AlGa_N/InGa_N heterostructures are displayed for the first time. The indium composition dependence of the electron

effective mass shows a nonlinear dependence for the entire indium concentration. This behavior was successfully explained through the introduction of the bowing term in the linear equation.

Chapter six shows the results and discussion of InGaAs/InAlAs inverted heterostructures. Anomalous CR splitting behavior related to Rashba effect was observed, and is explained perfectly through the theoretical calculation. Anti-crossing of the CR line in the vicinity of transverse-optical-phonon frequency and drastic change of the effective mass were also observed at high magnetic fields. These behaviors were discussed in details from the view point of induced special mode related to magneto plasmon-phonon mixing in high electron density regime. Conclusion and future work are presented in chapter seven.

CHAPTER TWO

Theoretical Background

2.1 III-V compound semiconductors

In the field of semiconductor, silicon (Si) and germanium (Ge) were the first materials to be exploited technologically. Si continues to be very important technological material. However, Si-based devices have some limitation, especially, for power- and opto-electronics application. This has led to intensive search for alternative semiconductors which have the possibility to overcome some setbacks of Si-based devices. For example [16], GaN has a large bandgap energy, leading to higher breakdown electric field than silicon, hence GaN has the possibility for high power devices application.

Table 2.1 Comparison of physical properties of some of the III-V semiconductors and silicon [17, 18].

Physical electronic properties	Si	GaN	GaAs	AlN	InN	InAs
Bandgap E_g (eV) at room temp.	1.1	3.5	1.4	6.2	0.7	0.4
Transition type	Indirect	Direct	Direct	Direct	Direct	Direct
Electron mobility μ (cm ² /Vs)	1,450	2,000	9,000	14	250	4,000
Breakdown field E_{br} (MV/cm)	0.3	2.5	0.4	1.8	–	0.04
Relative dielectric constant	11.8	10.4	12.8	9.14	9.3	12.4
Thermal conductivity (W/cm K)	1.0	2.5	2.0	3.19	0.38	0.27

Group III-V semiconductors have been one of the candidates that attracts attention as the potential materials for opto-electronic, power electronic and photovoltaic devices because of their semiconducting properties such as direct and wide bandgap energy (see Table 2.1). Examples of III-V semiconductors includes; gallium nitride (GaN), indium nitride (InN), gallium arsenide (GaAs), aluminium nitride (AlN) and their alloys such as InGaN and InGaAs. They can be grown in variety of

layers, hence, heterostructure based devices have been fabricated. Group III-V semiconductors are categorized into wurtzite and zincblende structures. This dissertation will focus on the GaN, InGaN and InGaAs semiconductors. In the following sections a brief overview of band structure and semiconducting properties will be given.

2.1.1 Band structure of wurtzite crystal

GaN contains hexagonal unit cell with six gallium atoms and six nitrogen atoms (see Figure 2.1). Each atom is surrounded by four nearest atoms. The Bravais lattice of the wurtzite crystal structure can be described by two lattice constants a and c , where a is the distance between the two adjacent atoms in the c -plane of the hexagonal unit cell and c is the distance between two successive A or B stacks along $[0001]$ direction [19,20]. Moreover, GaN is a direct and wide bandgap semiconductor (see Figure 2.2) commonly used in opto-electronics especially, light emitting diode and laser diode since the 1990s. Its wide band gap of 3.5 eV has the potential to afford a special property for applications in high-power and high-frequency devices. Thus, the performance of GaN-based devices is expected to far exceed Si- based devices used in the present electronics [20, 21].

The InN is another III-V semiconductor, it is rarely used in devices in its binary form. The InN can form wurtzite structure with direct and narrow bandgap energy of 0.7 eV (see Figure 2.3). InN combined with GaN (InGaN) can be suitable for future generation solar cells because the nitride alloy can cover wide range of solar spectrum range. The 2DES of InN have been realized recently, hence, it is possible to fabricate InN-based high electron mobility transistor in the future [15]. Moreover, AlN is another example of III-V semiconductors with some promising properties for future practical devices. So far, AlN represents the end point for the technologically important AlGaIn alloy. It is also used as a barrier layer for formation of AlGaIn/GaN heterostructures. As in the case of GaN, wurtzite lattice of AlN can be grown, and has the distinction of being the only Al-containing III-V

semiconductor with a direct energy gap (see Table 2.1). Additionally, it is among of the largest bandgap material with about 6.2 eV that is still commonly considered to be a semiconductor.

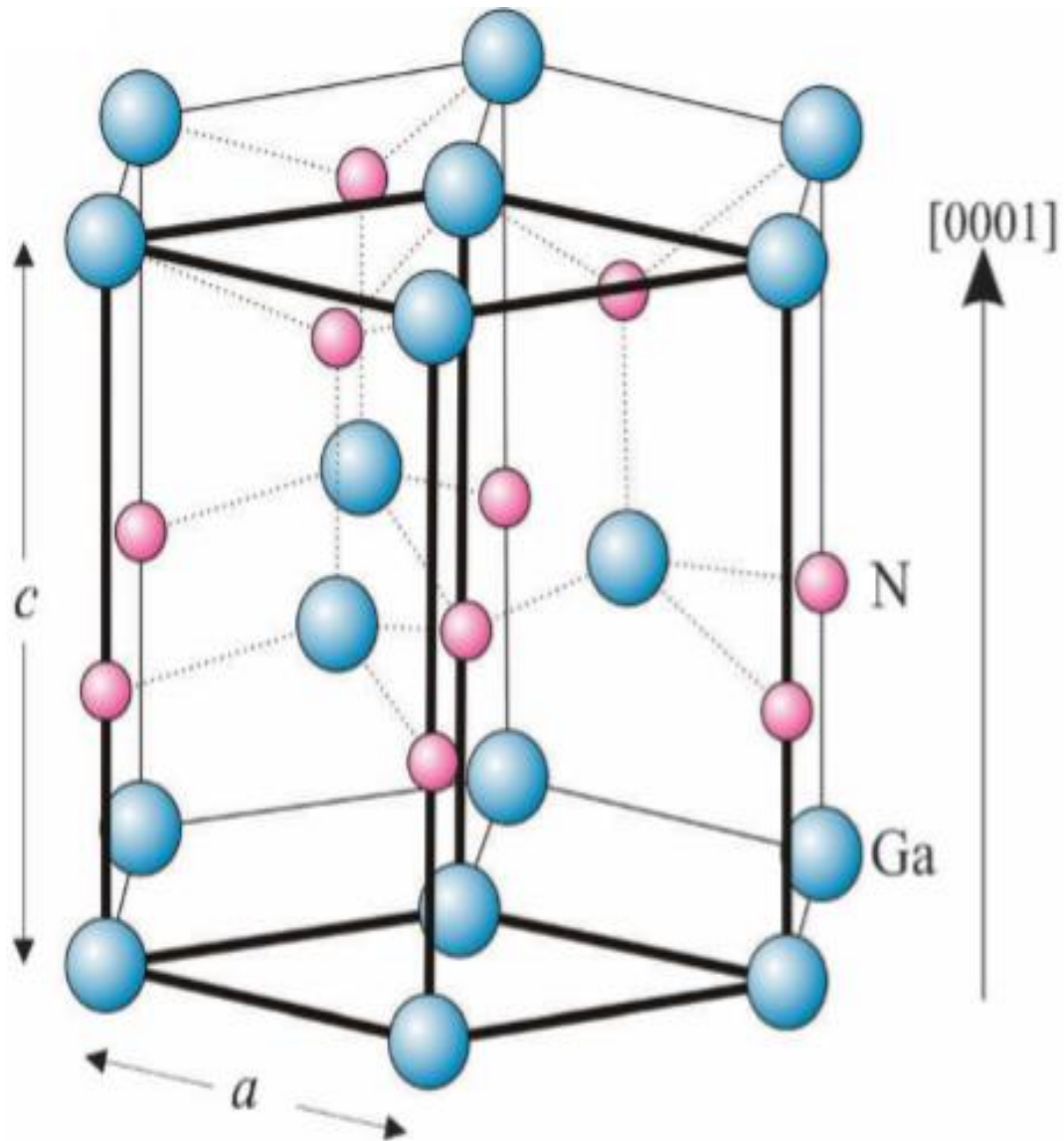


Figure 2.1 Wurtzite crystal structure of GaN. The hexagonal unit cell is shown with bold lines and the adjacent atoms are included to highlight the overall hexagonal nature of the structure. GaN bonds are indicated with dashed lines [19].

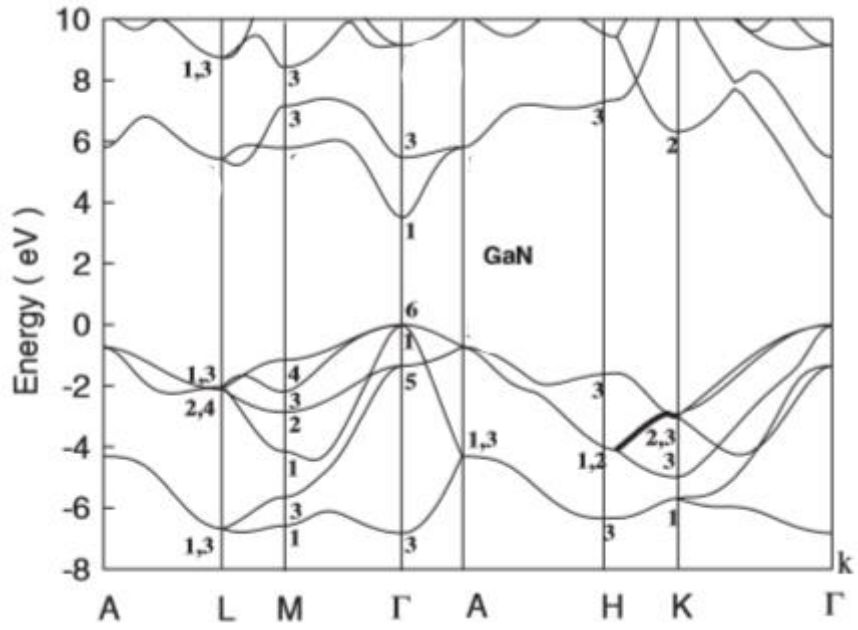


Figure 2.2. Band structure of wurtzite GaN. The band gap is located between 1 and 6 [21].

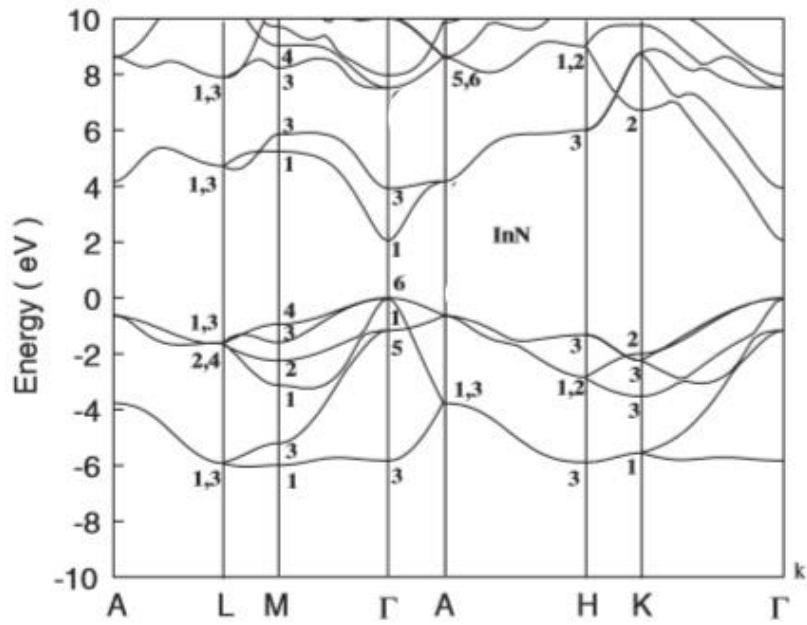


Figure 2.3 Band structure of wurtzite InN. The band gap is between 1 and 6 [21].

2.1.2 Band structure of zinc blend crystal

The GaAs and InAs are the typical example of semiconductors consisting zinc blend crystals [22, 23]. Figure 2.4 shows a typical zinc blende crystal of GaAs. The zinc blende crystal consists of two interpenetrating face-centered-cubic lattices, one having a group-III element atom, gallium (Ga) and the other one a group-V element atom, arsenic (As). A zinc blende crystal is characterized by a single lattice constant " a ".

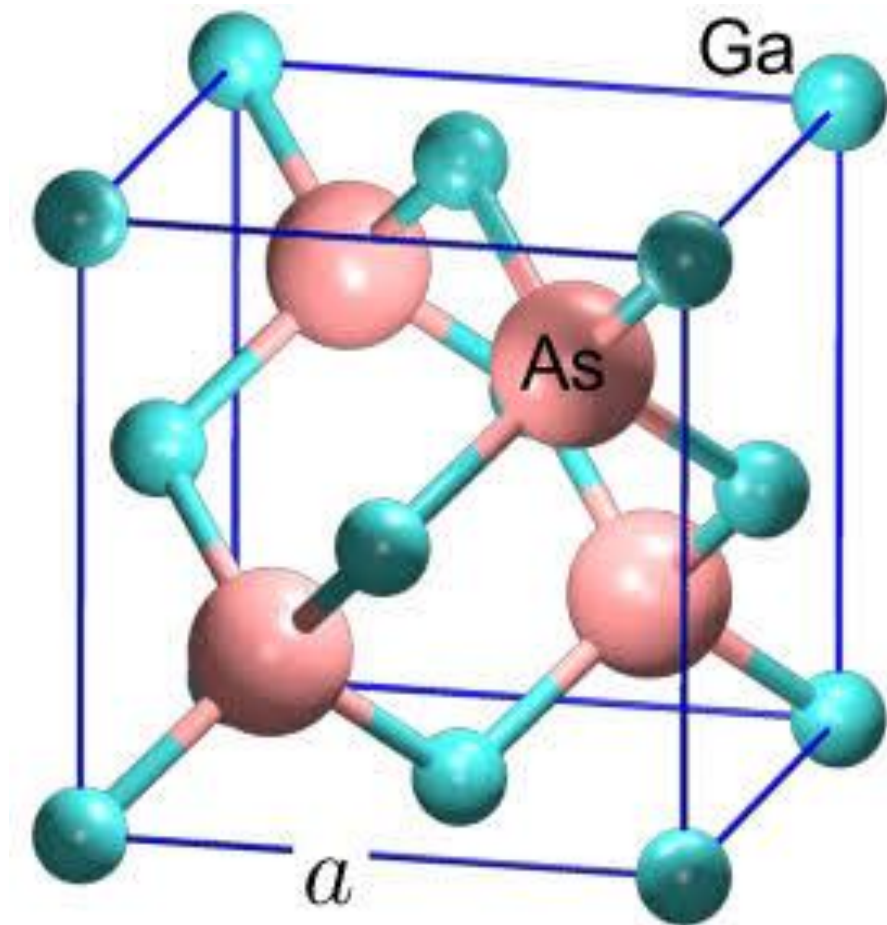


Figure 2.4 Typical zincblende crystal of GaAs [23].

In this dissertation, the zinc blende of InGaAs which is the direct and narrower band gap alloy formed through chemical architectures of GaAs and InAs (see Figure. 2.5) will be studied through the

CR measurements at high magnetic field. The InGaAs alloy is a key material in the active parts of high-speed electronic devices infrared lasers. It is a direct-gap material for the entire indium composition range because of lattice matching between InAs and GaAs [20].

2.1.3 Ternary alloys

InGaN and InGaAs are ternary alloys. These alloys are formed by combining a wide-gap semiconductor (e.g. GaN) and a narrow-gap semiconductor (e.g. InN) to form a semiconductor with desired intermediate band-gap (e.g. InGaN). Similar architecture for InGaAs which is the results of combination of GaAs and InAs semiconductors. As discussed, the previous sections, the InGaN and InGaAs have the potential for the application to photovoltaic and spintronics devices. For example, InGaN material is expected to provide high-efficiency InGaN-based solar cell devices because its ability to cover wide range of solar spectrum due to wide band gap energy (0.7 – 3.5 eV). Moreover, The InGaAs is the narrow band gap semiconductors with large spin-orbit interaction making it suitable for spin-device application.

In order to understand the band parameters of semiconductor alloy system and its composition dependence (example; $\text{In}_x\text{Ga}_{1-x}\text{N}$), Vegard's law have been used, and is given as [24]:

$$a(\text{In}_x\text{Ga}_{1-x}\text{N}) = (1-x) \cdot a(\text{GaN}) + x \cdot a(\text{InN}) \quad (2.1)$$

where a is the lattice constant of the binary materials. However, in many cases the band gap energy of ternary alloy is characterized by the bowing parameter b , which depends on composition and can be determined through the following relation;

$$E_g(\text{In}_x\text{Ga}_{1-x}\text{N}) = (1-x) \cdot E_g(\text{GaN}) + x \cdot E_g(\text{InN}) - bx(1-x), \quad (2.2)$$

where the bowing parameter b accounts for the deviation from a linear interpolation between the two binaries, for example GaN and InN. The bowing values for III-V alloys are typically positive indicating that the alloy band gap is smaller than the linear interpolation result. The bowing concept in the alloy-

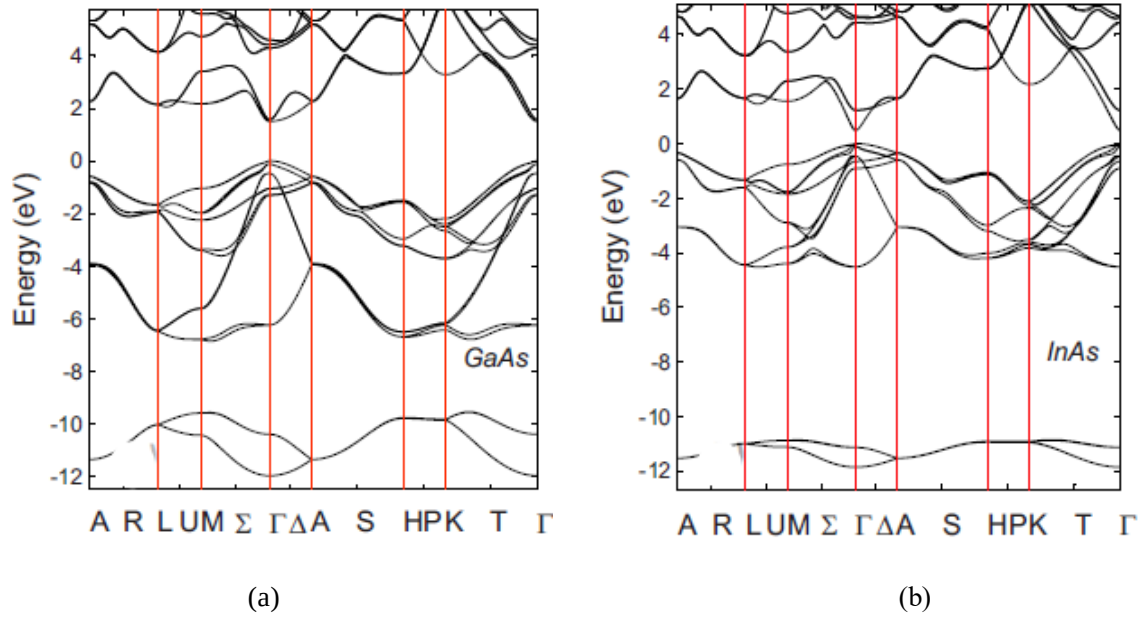


Figure 2.5. Typical band structure of zincblende crystal structures for (a) GaAs and (b) InAs [22].

composition has been generalized to include several other band parameters. The physical origin of the bowing behavior can be highlighted from the disorder effects created by the presence of different cations and anions. In other word, the lattice mismatch between the end-point binaries is another factor for bowing behavior.

2.2 Effective mass in semiconductor

The crystal structures of solid, in particular, semiconductors have been discussed in section 2.1. In solid-state physics, the band structure of material describes the range of energies an electron within the materials can contain. Through the band theory one can derive and determine various energy band related parameters including the bandgap energy and effective mass in a periodic lattice of atoms. Band theory has been successfully used to describe many physical properties of materials including electronic transport and optical absorption. This forms the foundation of understanding all electronic

devices such as diodes, transistors and solar cells.

In this section, band parameters such as the effective mass in solid are presented, especially, the effective mass which characterizes the ease with which an electron can be accelerated in crystals are discussed theoretically. Depending on the materials and purposes, sometimes the effective mass (m^*) can be considered to be a simple constant of a material, for example in bulk GaN and GaAs, the effective masses of electrons are $m^* = 0.2 m_e$ and $m^* = 0.067 m_e$, respectively. The value of effective mass depends on the purpose for which it is used, and can change depending on several factors such as electron-electron interaction, electron-phonon interaction, and band nonparabolicity.

In solid-state physics, the effective mass of electron or hole is usually stated in units of the rest mass of an electron, m_e . The value of rest mass of electron is estimated as 9.11×10^{-31} kg. In addition, the motion of an electron in periodic potential can be different from their motion in a vacuum. In general, the effective mass can be viewed as an important basic parameter that influences measurable properties of materials, including everything from the efficiency of a photovoltaic devices to the speed of an integrated circuit [25, 26].

In crystals, the conduction electrons/holes in semiconductors suffer from the periodic potential, $U(\mathbf{r})$. The periodic potential creates energy bands. Thus, this distinguishes free electrons from the conduction electrons/holes in semiconductors. The moving electrons through a periodic potential in crystals are well known as Bloch electron [27]. The periodic potential may be written as;

$$U(\mathbf{r}) = U(\mathbf{r} + \mathbf{R}), \quad (2.3)$$

where $\mathbf{r}$ is the electrons spacial coordinate and $\mathbf{R}$ is a lattice position vector. The single electron Hamiltonian in the potential $U(\mathbf{r})$ with the momentum $\mathbf{P} = -i\hbar \nabla$ and mass m is given as

$$H = -\frac{\hbar^2 \nabla^2}{2m} + U(\mathbf{r}) \quad (2.4)$$

Here, $-\frac{\hbar^2 \nabla^2}{2m}$ is the kinetic energy. The corresponding wave function based on single band is written;

$$\Psi_{nk}(\mathbf{r}) = e^{ik \cdot \mathbf{r}} u_{nk}(\mathbf{r}), \quad (2.5)$$

where, k is the wave vector, n is the band index, u_{nk} is the periodic function and Ψ_{nk} is the Bloch function which contains a periodicity of the lattice potential. The $e^{ik \cdot \mathbf{r}}$ is responsible for the free electron. The wave function obeys translational symmetry as

$$\Psi_{nk}(\mathbf{r}) = \Psi_{nk}(\mathbf{r} + \mathbf{R}) \quad (2.6)$$

Hence, equation (2.5) becomes,

$$\Psi_{nk}(\mathbf{r} + \mathbf{R}) = e^{ik(\mathbf{r} + \mathbf{R})} u_{nk}(\mathbf{r} + \mathbf{R}) \quad (2.7)$$

In most cases, the free electrons model can be applied to the motion of the Bloch electrons simply by replacing the mass m in equation (2.5) with the isotropic effective mass m^* , thus, in the vicinity of band extrema, the energy band $\mathcal{E}$ of the electron is expressed as parabolic band [25]:

$$\mathcal{E} = \frac{\hbar^2 \mathbf{k}^2}{2 m^*}, \quad (2.8)$$

In typical 3D system, when applied magnetic field, $B = 0$, equation (2.8) becomes;

$$\mathcal{E} = \frac{\hbar^2}{2 m^*} (k_x^2 + k_y^2 + k_z^2) \quad (2.9)$$

The effective mass of carrier is commonly expressed in units of the vacuum mass, m_e . At the edges of the Brillouin zone, where the band is not parabolic, large change of the effective mass value is expected. Figure 2.10 (a) shows the energy band dispersion of conduction electron. For small value of k , the energy of dispersion is parabolic with respect to k similar to free electrons with effective mass m^* . When k increases, the energy band deviates from the parabolic dispersion, and the effective mass appears to become heavier.

The effective mass, m^* in periodic potential is often approximated by the Schrodinger equation. The Schrodinger equation for an electron of mass m in the periodic potential $U(\mathbf{r})$ may be written as;

$$H\Psi = \left\{ -\frac{\hbar^2 \nabla^2}{2m} + U(\mathbf{r}) \right\} \Psi = \mathcal{E} \Psi. \quad (2.10)$$

H is the Hamiltonian (energy) operator, with $\mathbf{B} = 0$ (see equation (2.4)). In a very weak periodic

potential ($U(\mathbf{r}) = 0$), the Schrodinger equation (2.12) becomes;

$$H\Psi = \left\{ -\frac{\hbar^2 \nabla^2}{2m^*} \right\} \Psi = \mathcal{E} \Psi. \quad (2.11)$$

2.3 Quantum structures

When the dimension of a material is continuously reduced to a very small size, the properties will also change drastically. This is how a new structure of small sized material called nanostructure was formed. The typical examples of quantum structures include; quantum wells, quantum wires and quantum dots [28]. There are several ways in which such band structures with a certain property can be formed. One way is the use of semiconductor alloys, where a wide bandgap semiconductor and a narrow bandgap semiconductor are unified to form a semiconductor with a desired band gap energy. AlGaIn and AlGaAs are some of the examples of semiconductor alloys. Another example is the semiconductor superlattice or heterostructures, in which thin layer of different semiconductors are overlaid [28].

2.3.1 Growth of semiconductor multilayers

The growth of high-quality semiconductor multilayers is known as epitaxial. In this process layers are grown on a suitable single-crystal substrate, continuing the crystal structure of that substrate. MBE and MOCVD are well known techniques for the fabrication of high-quality epitaxial layers of semiconductors [28]. Detailed descriptions of MBE and MOCVD will be given in chapter three. High-quality single crystal substrates are used for growing semiconductor multilayers. Suitable substrate should consist one of the materials to be included in the multilayer. For example, in the case of GaAs growth, semi-insulating GaAs substrate is frequently used. The first layer to be grown is called buffer layer and is always similar but undoped materials as the substrate. Buffer layer is designed to provide an automatically-smooth top surface on which to grow the active parts of the multilayer. From this process, multilayer systems such as quantum well, superlattice and heterojunction can be fabricated,

and are briefly discussed as follows.

The quantum well is the simplest multilayer system, which consists of two heterointerface, meaning the structure is made up of more than one semiconductor. Here, a thick layer of wider bandgap crystal like AlGaAs is grown as a barrier layer, followed by a narrow bandgap crystal such as GaAs as the well layer, followed by another thick layer of wide bandgap material. Figure 2.6. shows the band profile of AlGaAs/GaAs heterostructures grown in the z -direction. The relative band energy gap (E_g) of discontinuities band off sets in the conduction band and the valence band shows the intrinsic characteristics of the two crystals used. The narrow bandgap crystal creates one-dimensional potential well in the conduction and valence bands. Thus, in the growth direction the electron and hole levels are bound states of the well called subbands. There are three types of

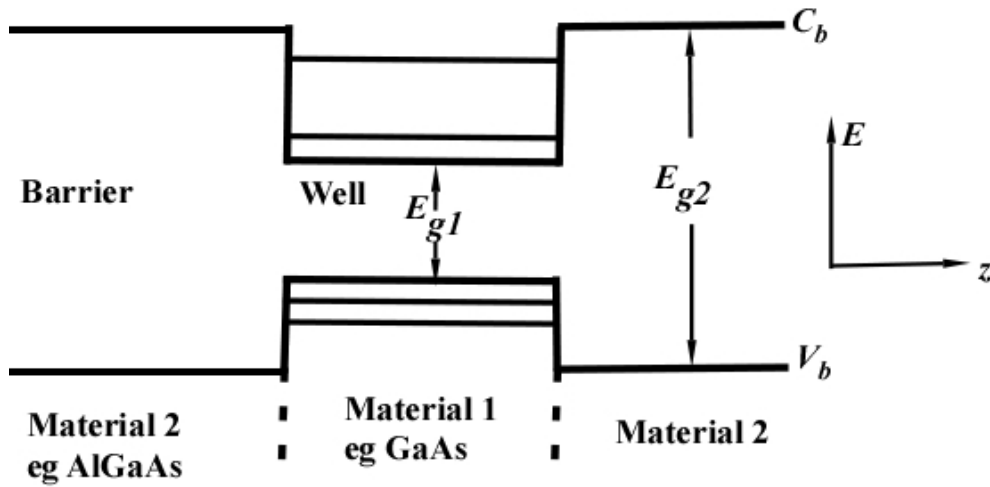


Figure 2.6 Band profile of quantum well as a function of thickness in the growth direction z . The energies of the subbands within the well are shown schematically.

subbands, namely; the electron subbands, the light-hole subbands and the heavy-hole subbands. The subbands are usually labeled and identified by a quantum number $i = 1, 2, \dots$. The motion in the xy plane

will be unrestricted, hence the well will contain two-dimensional carrier system.

On the other hand, heterojunction is a single junction formed between two layers of different semiconductors. A typical example includes; MgZnO/ZnO and AlGaAs/GaAs heterojunctions. Figure 2.7 shows band profile of AlGaAs/GaAs heterojunction. To obtain heterojunction, a thick layer of undoped GaAs is deposited first, followed by the spacer layer of AlGaAs. Then, a heavily doped AlGaAs is deposited, followed by additional undoped AlGaAs. The combination of the conduction band offset at the interface and the pinning of the Fermi energy inside the GaAs and AlGaAs layers results in a one-dimensional, roughly triangular potential well containing electrons which have dropped off from the donors of AlGaAs [20]. As in the case of quantum well, the electrons in z-direction motion will be quantized into subbands.

2.3.2 Two-dimensional semiconductors

The progress of epitaxial growth technology has made it possible to grow different type of structures with reduced dimensionality for various purposes. Low-dimensional semiconductors are attracting increasing interest because of their exciting optical and electronic properties. They are considered promising building blocks for the next generation of optical, sensing, electronic, and energy harvesting devices. Today, it is possible to generate 2DES (quantum well), 1DES (quantum wire) and even 0DES (quantum dot) structures for electrons, by confining them to a limited number of spatial dimensions. As their degree of freedom to move is condensed, it induces significant consequences for their interaction and kinetic behavior, thus opening up a new window for fundamental research and application.

The quantum well structure (2DES) occurs when one dimension is confined or reduced to the nanometer ranges while the other two dimensions remain large. The electrons are confined in one direction and can easily move in two-dimensions. Figure 2.7 shows typical example of 2DES

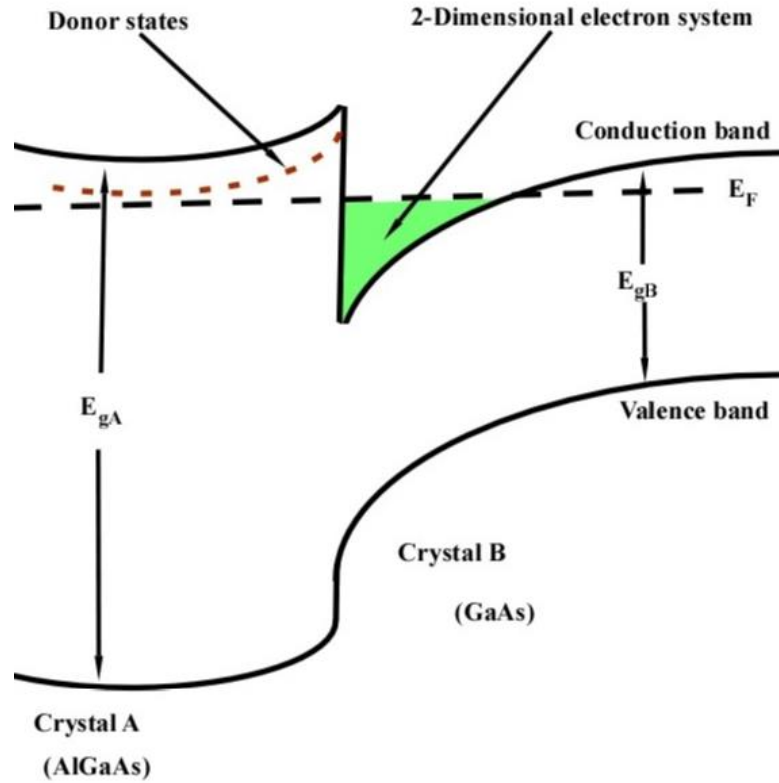


Figure 2.7 Energy profile of AlGaAs/GaAs heterojunction. The two-dimensional electrons system (2DES) is formed at the AlGaAs/GaAs interface due to modulation doping technique.

structures for AlGaAs/GaAs heterojunction. As discussed in chapter one, 2DES was first realized in Si-MOSFET in 1960s. Recently, the 2DES can be realized in many compounds such as GaAs, ZnO, GaN and InGaAs due to the progress of epitaxial growth techniques [7, 16, 28].

In low dimensional semiconductors, when magnetic fields are involved, they cause the conduction electron to conduct circular motion. Especially, in 2DES the circular plane is intrinsically defined. The intermediate position of 2DES in terms of freedom to move for the carriers makes them very interesting to study fundamental physics. As introduces in chapter one, this has led to the discovery of quantum Hall effect. This research work will focus on the study of electronic properties of 2DES of GaN, InGaN and InGaAs in the presence of high magnetic fields and low temperatures below 2K and

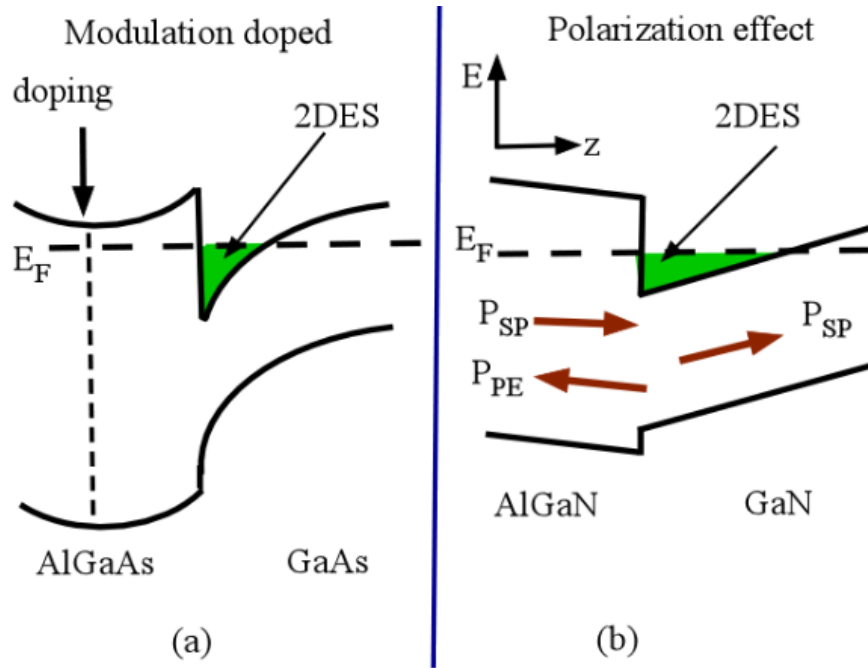


Figure 2.8 Energy band diagram showing different realizations of two-dimensional electron systems (2DES). (a) Standard modulation doping technique (b) Polarization technique. P_{PE} : piezoelectric polarization, P_{SP} : spontaneous polarization.

will be given in details in chapter three.

There are various methods for realizations of 2D systems, that follow different approaches on how the electrons are confined in one dimension. The most well-known way for formation of 2DES in semiconductors is the standard modulation doping technique. This technique was devised in Bell Labs in 1977 with the aim to reduce scattering effect associated with donor impurities in semiconductors. It has been used in compound semiconductors such as GaAs and its related materials for the realization of high electron mobility. In doped-GaAs heterostructures for example, the Si n-type donors have been successfully used as doping material and high carrier density was realized.

Figure 2.8 shows two different methods for the realization of two-dimensional electron systems. The AlGaAs/GaAs and AlGaN/GaN have in common, that a confinement potential is formed at the

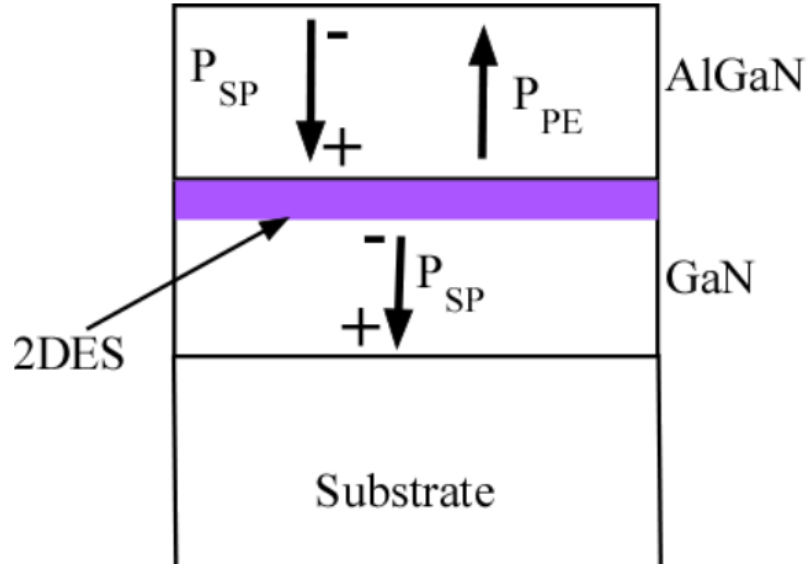


Figure 2.9 The formation of two-dimensional electron systems (2DES) in AlGaN/GaN

interface of two different materials. The energetic minimum in z -direction makes the electrons in the 2D plane. In standard modulation doping technique, the dopant (usually n -type Si-donor) is introduced on the wide bandgap material (AlGaAs) for formation of free electrons. These electrons, supplied by the Si-doping sheet, tunnel to the energetically favorable GaAs region. The charge redistribution creates a potential notch at the interface, where the electrons are trapped. Thus, the trapped electron creates the 2DES characterized by high mobility at the interface on the side of narrow bandgap material (GaAs) as shown in Figure. 2.8 (a). The introduction of spacer layer separates the donor states from the electrons reducing the scattering effect, thus the 2DES is characterized by high mobility properties. Essentially this high mobility 2DES makes the sample a suitable choice to study cyclotron resonances.

On the other hand, as discussed in the previous section, GaN, AlN and InN are polar materials with wurtzite crystal structure which have an intrinsic spontaneous polarization and piezoelectric fields. The two-dimensional electron systems are accumulated at the heterointerface due to large spontaneous and piezoelectric polarization effects without the standard modulation doping technique

(Figure 2.8 (b)). For example, the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ and GaN have different magnitude of the polarization field (see Figure 2.9). It is exactly this polarization field mismatch which is exploited in $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ and $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{InGaN}$ heterostructures to form a two-dimensional electron system at the heterointerface on the side of narrower bandgap materials (GaN and InGaN). Moreover, due to charge accumulation at the interface and the accompanying electrostatic forces a triangular shaped potential notch is created by the GaN and/or InGaN conduction band in addition to the band-offset at the interface [6]. Thus, both standard modulation and polarization field have been used for fabrication of high electrical mobility transistors for the fast operation systems.

2.4. Classical Drude model

The Drude model was the first attempt to utilize the idea of free electrons (gas) moving between positively charged ionic cores in order to describe the properties of metal. The Drude model is one of the important model because it provides information on electrons in a crystal as free particles [27, 29, 30]. Drude model gives a comparatively approach to the dynamics of the electrons. From Drude model the electron mobility μ and the electron scattering time τ were originally defined. Electrons are accelerated by an electric field $\mathbf{E}$, associated with a voltage drop V across the materials. Because of different scattering processes the electron undergoes momentum changes and energy losses, and averaging them gives out an overall drift velocity. Here, the assumption is, all electrons are equally contributed to the transport and scattering events, and they are homogenous and isotropic. Moreover, the motion of electrons in a magnetic field, $\mathbf{B} \neq 0$ and electric field $\mathbf{E}$ is described by the following classical equation of motion [29, 30, 31].

$$m^* \frac{d\mathbf{v}}{dt} + m^* \frac{\mathbf{v}}{\tau} = -e\mathbf{E} - e(\mathbf{v} \times \mathbf{B}) \quad (2.12)$$

where τ is the time between two scattering events, and its effect is taken into account by the second term in the left side. In steady state, $\frac{d\mathbf{v}}{dt}$ vanishes, when $\mathbf{B} = 0$, the group velocity becomes $\mathbf{v} = \frac{e\tau}{m^*} \mathbf{E}$.

The scattering time is often expressed by the means of the electron mobility as,

$$\mu = \frac{e\tau}{m^*} \quad (2.13)$$

Here the electron mobility μ is a measure for the conductivity of electrons. Thus, the effective mass can be interpreted as a measure of how easily the electron can be accelerated, and the scattering time τ of how much it is decelerated by scattering processes.

It is good to note that τ can be addressed by improving the crystal quality. However, in general, the electrons in semiconductors involve many types of scattering process such as alloy scattering, phonon scattering, interface scattering and roughness scattering. The total scattering probability can be explained by the sum of all possible scattering probabilities and the total relaxation time τ^{-1} is given by

$$\frac{1}{\tau} = \sum_j \left(\frac{1}{\tau_j} \right) \quad (2.14)$$

Hence, the electron mobility in equation (2.13) accounts for the total of all scattering events.

The moving electron with carrier concentration, n_s and mobility μ directly relates the current density j to the applied voltage $= \frac{E}{d}$, (d is the sample thickness) and this describes the electrical resistivity ρ as

$$\rho = \frac{E}{j} = \frac{E}{n_s e v} = \frac{1}{n_s e^2 \tau m^*} = \frac{1}{n_s e \mu} \quad (2.15)$$

Experimentally the resistivity $\rho = \sigma^{-1}$ is measured using a current with known resistor in series, and measuring the voltage drop across the sample. The resistance R can be defined in terms of resistivity ρ as

$$R = \rho \frac{L}{A} \quad (2.16)$$

Here L is the sample length and A the sample cross-sectional area. In the case of ideal 2D systems (special case), $L = A$, thus, $R = \rho$. The conductivity connects the current (density) through the sample and the applied electric field, $j = \sigma E$ and is measured by applying a voltage and measuring the current

through the sample. when $B = 0$, the conductivity of material can be defined in terms of effective mass through the following relation,

$$\sigma = \frac{n_s e^2 \tau}{m^*} \quad (2.17)$$

When magnetic field is applied, the conductivity will become a tensor rather than a scalar. In addition, when a current is passed through a sample with magnetic fields applied perpendicular, a Hall voltage is developed to compensate for the Lorentz force, and it is described by the Hall resistivity $\rho_H = \frac{B}{n_s e}$.

2.5 Electron motion in magnetic fields

2.5.1 Landau levels

Figure 2.10 (b) shows the energy band dispersion of conduction electron in a magnetic field. As discussed in the previous sections, when $B \neq 0$, electron's motion is quantized in the x,y plane perpendicular to the magnetic field, resulting into Landau levels. This means that, ϵ is quantized into Landau levels along xy-direction while z-direction will remain unquantized. This can be expressed by;

$$\mathcal{E} = \left(N + \frac{1}{2}\right) \hbar \omega_c + \frac{\hbar^2 k_z^2}{2 m^*}. \quad (2.18)$$

The above results are summarized in Figure 2.10. The energy band with $B = 0$, is shown on the left-hand side, and the energy band when magnetic field is applied in the z-direction ($B \neq 0$) is shown in the right-hand side. In 2D system, with $B = 0$, the energy bands may be given as[29, 31].;

$$\mathcal{E} = \frac{\hbar^2 \mathbf{k}^2}{2 m^*} = \frac{\hbar^2}{2 m^*} (k_x^2 + k_y^2). \quad (2.19)$$

And when $B \neq 0$, $\mathcal{E}$ is quantized into Landau levels in the xy-direction as shown in Figure 2.10 (b).

When $B \neq 0$, equation (2.10) may be written as

$$H = \frac{1}{2m} (\mathbf{P} - e\mathbf{A})^2 + U(\mathbf{r}) \quad (2.20)$$

Here, $\mathbf{A}$ is the vector potential, $\mathbf{A} = (0, Bx, 0)$, $\mathbf{B} = \nabla \times \mathbf{A}$, and $\mathbf{B} = (0, 0, B)$,

and momentum $\mathbf{P} \rightarrow -i\hbar \nabla$, hence,

$$\frac{p^2}{2m} \rightarrow -\frac{\hbar^2 \nabla^2}{2m}, \quad (2.21)$$

Equation (2.19) tells us that the Landau levels in the conduction band, which has a parabolic energy dispersion, have the same energy as free electron. In addition, equations (2.19) and (2.21) are widely applicable for understanding properties of many semiconductors indicating that the effective mass is very important.

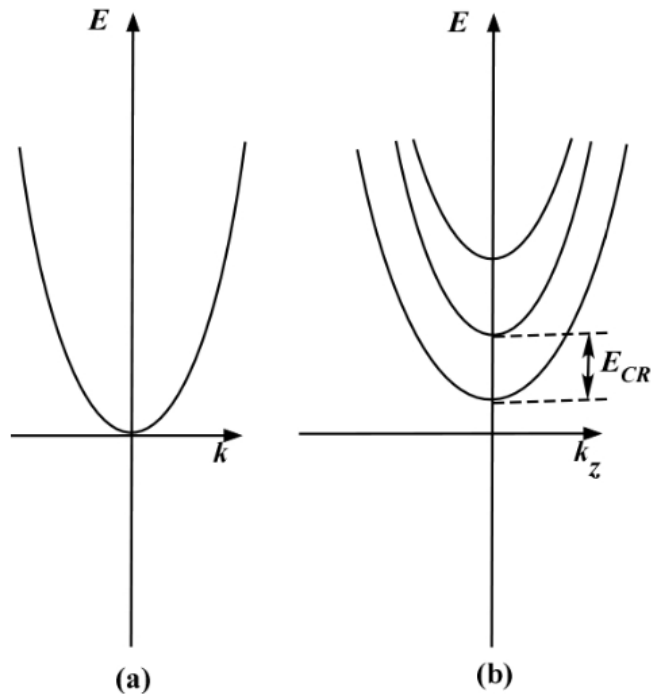


Figure 2.10 Electronic states for 3D electron systems. (a) appearance of energy band without magnetic field ($B = 0$). (b) Energy band with magnetic field ($B \neq 0$), electrons are quantized in a plane perpendicular in the magnetic field, resulting into landau levels ($\mathcal{E}_{CR} = \hbar\omega_c$).

Furthermore, with the influence of magnetic field B directed perpendicular to the 2DES the density of states splits up in a discrete set of Landau levels per subband N with energies,

$$\mathcal{E} = \left(N + \frac{1}{2}\right) \hbar \frac{eB}{m^*} \pm \frac{1}{2} g^* \mu_B B \quad (2.22)$$

Where u_B is the Bohr magneton, the $\pm$ takes account of spin-up and spin-down electrons and g^* is the effective g-factor. It follows from equation (2.22) that the energy between the Landau levels is proportional to the applied magnetic field B . In order to observe the quantum Hall effect the energy splitting of the Landau levels should be much larger than the thermal broadening of a single Landau levels, $\hbar\omega_c \gg k_B T$. This requires typically the experiments to be carried out at low temperatures. The number of occupied Landau levels is called the filling factor ν . The filling factor ν is a number of filled (spin-split) half Landau levels, and is related to the magnetic field by [29, 31].

$$\nu = \frac{\hbar n_s}{eB} \quad (2.23)$$

By increasing the magnetic field, the Landau levels are successively pushed to above E_F , which gives rise under quantum Hall conditions to the plateau-plateau transitions. When the Fermi level is located between two Landau levels R_{xy} attains a plateau value and $R_{xx} = 0$. Ideally the quantum Hall transitions occur at filling factors $(N + 1/2)$, where $N = 0, 1, 2, \dots$

The Landau levels can be explained by considering the quantization of energy levels. From the Hamiltonian with the Landau gauge $A(0, Bx, 0)$,

$$H = \frac{1}{2m} (\mathbf{P} - e\mathbf{A})^2 = \frac{p_x^2}{2m} + \frac{(p_y - eBx)^2}{2m} + \frac{p_z^2}{2m}. \quad (2.24)$$

The Schrödinger equation is

$$H\Psi = \mathcal{E}\Psi. \quad (2.25)$$

$$\Psi = e^{ik_z z} f(x, y), \quad (2.26)$$

to obtain

$$\mathcal{E} = \mathcal{E}_z + \mathcal{E}_\perp, \quad \mathcal{E}_z = \frac{\hbar^2}{2m} k_z^2 \quad (2.27)$$

$$\frac{1}{2m} (p_x^2 + p_y^2) f(x, y) = \mathcal{E}_\perp f(x, y), \quad (2.28)$$

$$\left(\frac{p_x^2}{2m} + \frac{(p_y + eBx)^2}{2m} \right) f(x, y) = \mathcal{E}_\perp f(x, y). \quad (2.29)$$

The function can be separated as

$$f(x, y) = e^{ik_y y} \varphi(x). \quad (2.30)$$

Then the equation for $\varphi(x)$ is

$$\left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x^2} + \hbar \omega_c k_y x + \frac{m \omega_c^2}{2} x^2\right) \varphi = \left(\mathcal{E}_\perp - \frac{\hbar^2 k_y^2}{2m}\right) \varphi. \quad (2.31)$$

If we define

$$X = -k_y l^2, \quad (2.32)$$

And then put;

$$x = x' - k_y l^2 = x' + X. \quad (2.33)$$

Then,

$$\left(-\frac{\hbar^2}{2m} \frac{\partial^2}{\partial x'^2} + \frac{m \omega_c^2}{2} x'^2\right) \varphi(x) = \mathcal{E} \varphi(x). \quad (2.34)$$

The solution of this one-dimensional differential is

$$\varphi(x) = \Phi_N\left(\frac{x-X}{l}\right) \quad N = 0, 1, 2, \dots \quad (2.35)$$

And,

$$\Phi_N(x) = C_N \exp\left(\frac{x^2}{2}\right) H_N(x), \quad (2.36)$$

is a Harmonic oscillator function with the Hermite polynomials,

$$H_N(x) = (-1)^N e^{x^2} \frac{\partial^N}{\partial x^N} (e^{-x^2}). \quad (2.37)$$

The first few lowest order functions are

$$H_0(x) = 1, \quad H_1(x) = 2x, \quad H_2(x) = 4x^2 - 2, \dots \quad (2.38)$$

The quantized energy is

$$\mathcal{E}_\perp = \left(N + \frac{1}{2}\right) \hbar \omega_c. \quad (2.39)$$

The radius r_c of the cyclotron motion is for the N-th state is given by

$$r_c^2 = (x - X)^2 + (y - Y)^2 = (m \omega_c)^{-2} (p_x^2 + (p_y + e B_x)^2) = \frac{2\hbar \left(N + \frac{1}{2}\right)}{m \omega_c}. \quad (2.40)$$

Therefore,

$$r_c = (2N + 1)^{\frac{1}{2}}l. \quad (2.41)$$

Here, l is the magnetic length defined as the distance between the two magnetic poles. Note that r_c and l are independent of any material parameters like m^* , uniquely determined by magnetic field.

2.5.2 Cyclotron resonance

Magnetic field is a powerful tool for understanding and analyzing electronic properties of materials through measuring their band structure. In magnetic fields the electronic motion of materials is partially quantized into Landau levels, making it possible to obtain various electronic information such as the effective mass. Such kind of technique for measuring the band structures of materials is known as Landau quantization or cyclotron motion which was discussed in chapter two. High magnetic fields are beneficial in various ways for cyclotron resonance. Firstly, as a necessary condition of the cyclotron resonance, $\hbar\omega_c > 1$ can be satisfied even in low mobility materials. Furthermore, the cyclotron energy can exceed various excitation energies in semiconductors including LO-phonons, plasmons and the energy bandgap [31].

Cyclotron resonance (CR) is a powerful technique for obtaining the effective mass and scattering time of carriers in semiconductors directly, and to study energy band structure, electronic states, electron interaction with other excitations. The effective mass of major semiconductors such as Si, Ge, and GaAs have already been determined by using this technique. The CR is also used for understanding the energy band structure, electron interaction with another excitation, and electron states [31]. This technique involves making a direct measurement of ω_c using millimeter-wave or far-infrared radiation to excite an electron between Landau levels. The condition for observing the CR in metals and semiconductors are somewhat different because of the number densities they possess, and the CR in metals is beyond the scope of this thesis.

In semiconductors, the carrier concentrations are much lower than those in metal, hence the

radiation whose energy is below the band gap can completely penetrate even large samples. The CR arrangement for semiconductors measurement is described in detail in chapter three. The CR is usually carried out by measuring the sample transmission. There are two ways to observe CR in semiconductors. One is by fixing the magnetic field constant while varying the energy of radiation, magnetic field is usually provided by a super-conducting magnet. The other one is by sweeping magnetic fields at fixed frequency source such as far-infrared laser [12]. In the case of high magnetic fields application, the resonance frequency in most semiconductors lies in the terahertz (THz) range. Consequently, the THz spectroscopy or far-infrared method is essential.

The first observation of CR in semiconductors such as Si and Ge were found in early 1950s [28-30], and since then, CR has been used for estimating the effective of semiconductors, understanding various phenomena such as carrier scattering mechanisms and effect of carrier-phonon interactions on effective masses. When the conduction electron with charge e and effective mass m^* , is placed in a magnetic field B , the electron will make circular motion in the plane perpendicular to B with angular frequency $\omega_c = \frac{eB}{m^*}$. The circular motion is due to Lorentz force perpendicular to B . As the whole of the cyclotron orbit experiences the electric field of radiation, the cyclotron motion resonantly absorbs the energy when the angular frequency of radiation ω coincides with ω_c .

$$\omega = \omega_c = \frac{eB}{m^*} \quad (2.42)$$

This phenomenon is called CR which can be represented well by classical dynamic of electrons in magnetic fields and electromagnetic radiation shown in the previous section.

The line width of the resonance gives the information about the scattering rate τ^{-1} , indicating that in semiconductors there exist various scattering processes which induce uncertainties to the cyclotron frequency [32];

$$\omega_c \approx \tau^{-1} \quad (2.43)$$

The condition for observing well-defined CR is presented by

$$\omega_c \tau \geq 1 \quad (2.44)$$

This means that there will be smearing out of the CR, hence, resonant absorption will not be observed when the condition (2.44) is not fulfilled. Equations (2.43) and (2.44) tell us that, to observe clear CR, high magnetic field is necessary or by lessening τ through lowering the temperature of the sample during experiments. In addition, combining equations (2.40), (2.43) and (2.44) and rearranging give

$$\omega_c \tau = \frac{eB}{m^*} \tau = \mu B \geq 1 \quad (2.45)$$

Equation (2.45) can be written as

$$\omega_c \tau = \mu B \geq 1 \quad (2.46)$$

The electron mobility becomes higher at lower temperatures where less phonon scattering occurs. At low temperatures carriers are captured by acceptors or donors, there will be no free carriers for absorbing the radiation field. However, in the case of 2DES free carriers exist even at low temperatures. The mobilities can be categorized into, but not limited to, alloy mobility, polar optical phonon mobility, piezoelectric mobility and neutral impurity mobility.

2.5.3 Cyclotron resonance in 2DES

The discovery of two-dimensional electron system (2DES) in Si-MOSFET in 1960s, came with many interesting features for extensive fundamental research [33, 34]. This Si-MOSFET was utilized as semiconductor for electronic devices, and also it offered window for study electronic properties of the 2DES. One of such studies is CR measurements. The first CR experiment of 2DES in Si-MOSFET was reported in 1974s. The sample were grown such that, in the Faraday configuration a transverse mass is obtained, and the value was almost similar to the bulk sample. The effective mass for Si-MOSFET were reported between $m^* = 0.20m_0$ to $0.21m_0$ which is in good agreement with the mass from bulk sample, $m^* = 0.19m_0$ [32, 35, 36].

In 2D electron system, numerous CR experiments have been performed with aim to determine

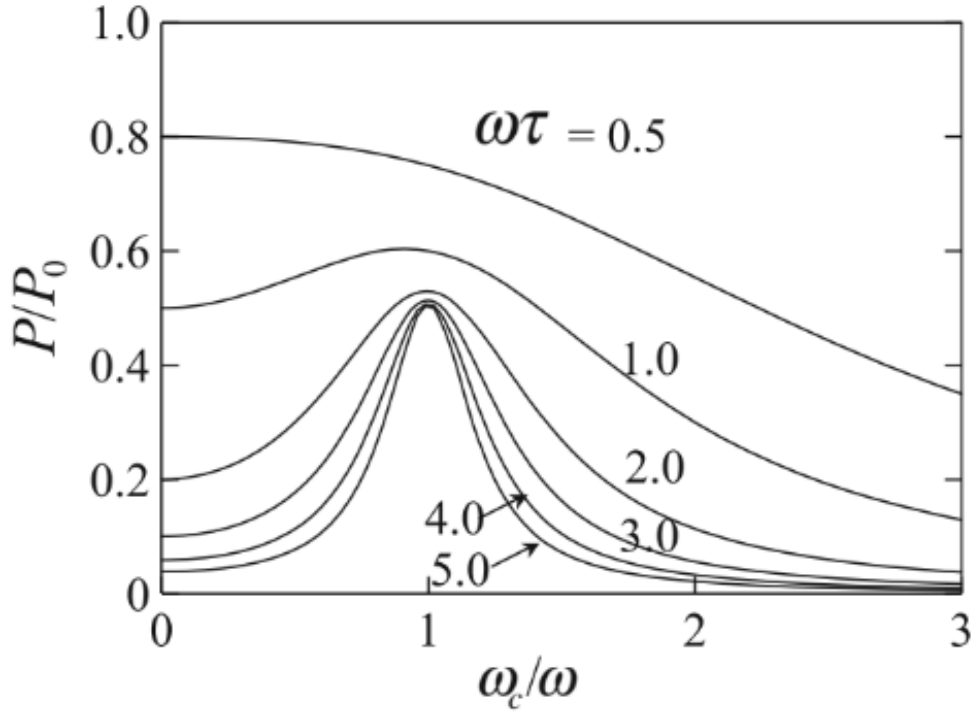


Figure 2.11 Absorption line shapes of the CR curves at different values of $\omega\tau$ [31].

the effective mass as well as to explore the new effects since the early days [35]. Various features, for example the polaron effect, band non-parabolicity and others have been explored from the detailed studies of the CR, and they all shows different characteristics from the 3D case. The carrier concentration dependence of the effective mass, magnetic field dependence of the CR energy and magnetic field dependence of the CR mass are among of the many features discovered from the CR study in 2D systems [14, 36 - 38]. Recently, Syed *et al* [14] investigated CR in wide range of carrier concentration while looking for the effective mass enhancement from the band edge mass in GaN 2D systems. It was found that the band non-parabolicity is the major factor for the mass enhancement. The CR study in polar materials such as II-VI semiconductors which have large coupling constant, the polaron effect was found to be a key factor for understanding the effective mass.

2.5.4 Cyclotron resonance absorption

As shown in the previous sections, the motion of electrons in magnetic field $\mathbf{B}$ and electric field $\mathbf{E}$ is presented by the following classical equation of motion

$$m^* \frac{dv}{dt} + m^* \frac{v}{\tau} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \quad (2.47)$$

Where the effect of electrons scattering is taken into account through the second term in the left side of the equation by relaxation time τ . Consider a case where magnetic field is applied parallel to the z -direction such that $\mathbf{B} = (0, 0, B)$, and the radiation field with angular frequency ω will also propagate along the z -direction. Then the electric field will be linearly polarized with $\mathbf{E} = (E_x, 0, 0)$ perpendicular to the z -axis [31]. The radiation field with ω can be expressed as

$$E = E_x \cos(\omega t) = \text{Re}(E_x \exp(-i\omega t)) \quad (2.48)$$

Using the relation;

$$\frac{d}{dt} = -i\omega \quad (2.49)$$

together with equation (2.48), the equation of motion (2.47) leads

$$m^* \left(-i\omega + \frac{1}{\tau}\right) v_x = e(E_x + v_y B_z) \quad (2.50)$$

$$m^* \left(-i\omega + \frac{1}{\tau}\right) v_y = e(0 - v_x B_z) \quad (2.51)$$

And the carrier velocity v_x and v_y are obtained from equations (2.50) and (2.51) as

$$v_x = \frac{e\tau}{m^*} \cdot \frac{(1-i\omega\tau)}{(1-i\omega\tau)^2 + \omega_c^2 \tau^2} E_x \quad (2.52)$$

$$v_y = \frac{e\tau}{m^*} \cdot \frac{i\omega\tau}{(1-i\omega\tau)^2 + \omega_c^2 \tau^2} E_x \quad (2.53)$$

As the current density in the x -direction is given by

$$J_x = nev_x \quad (2.54)$$

The power absorption P of the radiation per unit volume is given as

$$P = \frac{1}{2} \text{Re}(J_x E_x) = \frac{1}{2} \frac{ne^2 \tau}{m^*} E_x^2 \text{Re} \left(\frac{(1-i\omega\tau)}{(1-i\omega\tau)^2 + \omega_c^2 \tau^2} \right)$$

$$\begin{aligned} &\equiv \frac{1}{4} \sigma_o E_x^2 \text{Re} \left(\frac{1}{(1 - i\omega\tau) - i\omega_c\tau} + \frac{1}{(1 - i\omega\tau) + i\omega_c\tau} \right) \\ P &= \frac{1}{4} \sigma_o E_x^2 \left(\frac{1}{(\omega - \omega_c)^2 \tau^2 + 1} + \frac{1}{(\omega + \omega_c)^2 \tau^2 + 1} \right) \end{aligned} \quad (2.55)$$

Here, Re denotes the real part, ω_c is the cyclotron angular frequency and $\sigma_o = \frac{ne^2\tau}{m^*}$ is the conductivity of semiconductors when n is the carrier concentration.

Figure 2.11 shows the shape of the absorption curve similar to equation (2.55). This is called Lorentz function. In Figure 2.11, it is clear that the absorption has a peak at $\omega/\omega_c = 1$, and the width of the peak decreases as $\omega\tau$ is increased. The peak is clearly observed when $\omega\tau > 1$. This is the necessary condition for observing cyclotron resonance, and this means that the carriers should complete at least one cyclotron orbit between the scatterings. The background is more noticeable for small $\omega\tau$. In the case of purely 2D electron systems, like the CR absorption in graphene, one usually has to deal with a complete approximation of the magneto-transmission of the multilayer system. In most case, this standard approach can be simplified to a theoretical model, which assumes a purely 2D electron gas located between the vacuum and a dispersionless polar medium. If the only resonant absorption emanates from the 2D layer, the transmission T may be given as [39]:

$$T(\omega, B) = \frac{T_+(\omega, B) + T_-(\omega, B)}{2T(\omega, B=0)} \quad (2.56)$$

Equation (2.56) is usually characterizes by refractive index n of the materials which may be approximated as;

$$T_{\pm}(\omega, B) = \frac{16n^2}{|\alpha_{\pm}(\omega, B)|^2 - |\beta_{\pm}(\omega, B)|^2} \quad (2.57)$$

Where the $\pm$ sign corresponds to right- and left-handed circular polarizations, $\omega = \omega_c = \frac{eB}{m^*}$ is the cyclotron frequency and;

$$\alpha_{\pm}(\omega, B) = (n + 1) \left(n + 1 + \frac{\sigma_{\pm}(\omega, B)}{\epsilon_o c} \right) \quad (2.58)$$

$$\beta_{\pm}(\omega, B) = (n - 1) \left(n - 1 - \frac{\sigma_{\pm}(\omega, B)}{\epsilon_o c} \right) \quad (2.59)$$

Here c is a speed of light, n is the refractive index and ϵ_0 is the dielectric constant of material in vacuum. The dynamic conductivity σ of materials is defined by the equation (2.39).

2.6 Magneto-transport phenomena

Magneto-resistance is the tendency of materials to change their resistivity and conductivity as a result of application of external magnetic field. In this section, magneto-resistance in semiconductors is discussed. Hall effect is introduced first, in-line with the subsequent discovery of quantum Hall effect, finally description on Shubnikov-de Haas oscillation will be is given.

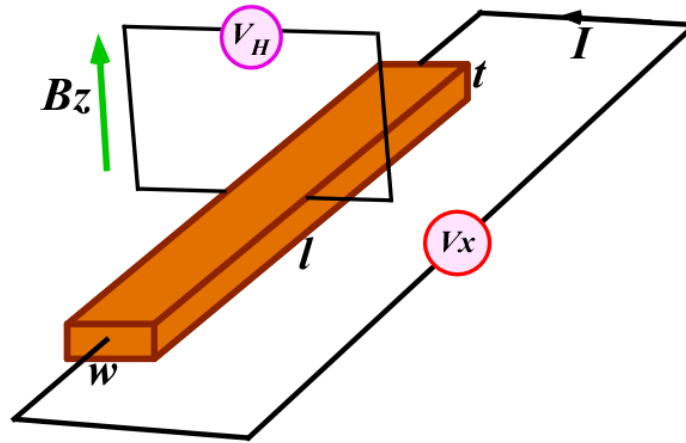


Figure 2.12 Schematic representation of the classical Hall effect

2.6.1 Hall effect in semiconductors

The Hall effect occurs when a magnetic field (B) is applied perpendicular to a thin conducting sample through which a current (I) is flowing (see Figure 2.12). A Hall voltage (V_H) is produced in a direction perpendicular to both current and magnetic field. This phenomenon was discovered by Edwin Hall in the 1879, and it has led to the discovery of many other phenomena such as quantum Hall effect, fractional quantum Hall effect and integer quantum Hall effect.

In principal, the Hall voltage is caused by the Lorentz force acting on the charges moving in the presence of a magnetic field. In equilibrium the Lorentz force $F_L = ev_d B$ is balanced by the electric force eV_H/w , where e is the electronic charge, $v_d = E/B$ is the drift velocity which indicates that apart from circular motion, electrons never move in the direction parallel to the electric field E in a long-term average and w is the width of the sample. Hence, $V_H = v_d w B$ exhibits a linear dependence on the magnetic field B . When both magnetic field and electric field are present, the total force acting on an electron can be written as

$$f_e = -e\mathbf{E} - ev \times \mathbf{B} \quad (2.60)$$

Equation (2.60) may written as [29, 30];

$$\frac{dv}{dt} = -\frac{e}{m_e}\mathbf{E} - \frac{e}{m_e}v \times \mathbf{B} - \frac{v}{\tau} \quad (2.61)$$

The last term of equation represents the scattering of electrons by various mechanisms with a relaxation time of τ . If magnetic field is in the z -direction and the electric field is in the x -direction, equation (2.61) is reduced to;

$$v_x = -\frac{e\tau}{m_e}E_x - \omega_c \tau v_y \quad (2.62)$$

$$v_y = -\frac{e\tau}{m_e}E_y + \omega_c \tau v_x \quad (2.63)$$

Where $\omega_c = \frac{eB}{m_e}$ Since there is no current in the y -direction, $v_y = 0$, then equations (2.62) and (2.63)

can be combined and simplified to give

$$\frac{E_y}{E_x} = \omega_c \tau \quad (2.64)$$

The current density flowing through a sample can be written as $J_x = -en_s v_x$ then equations (2.62) and (2.63) can be combined to form,

$$R_H \equiv \frac{E_y}{J_x B} = -\frac{1}{en_s} \quad (2.65)$$

Where R_H is known as Hall coefficient or Hall-resistance (R_{xy}) which was predicted by the Drude

model.

The Hall coefficient R_H is independent of both magnitude of B and scattering time τ . However, in reality, R_H varies with magnetic field. Therefore, since R_H depends on the magnetic field B and the carrier density the Hall effect has become a standard tool of material characterization.

2.6.2 Quantum Hall effect

The quantum Hall effect (QHE) is the epoch-making phenomenon observed in two-dimensional electron system subjected to low temperatures and high magnetic fields. The discovery of the ordinary Hall effect and advent of the quantum Hall effect are one century apart. The quantum Hall effect which was observed firstly in silicon metal oxide semiconductor in 1980 by professor von Klitzing has already led to two Nobel prizes in physics, one for the integer quantum Hall effect in 1985 [1] and one for the fractional quantum Hall effect in 1998 [2, 3].

These robust quantum phenomena on a macroscopic scale Hall effect manifest themselves in the transport parameters of the two-dimensional electron gas that are directly measurable, notably the longitudinal resistance R_{xx} and the Hall resistance R_{xy} . Figure 1.2 shows a typical fractional QHE in MgZnO/ZnO heterostructures. The quantum Hall effect is standard observed in high magnetic fields B and at low temperatures and it is well known that the phenomenon only exists because of the breaking of translational invariance by random impurities. Instead of the linear dependence of R_{xy} with varying magnetic field B , it now turns out that the Hall resistance is quantized in units of h/e^2 . In the fractional quantum Hall effect, which is observed only in the very high-quality samples, an additional plateau occurs at [4];

$$R_{xy} = \frac{V_y}{I} = \frac{1}{i} \frac{h}{e^2} = \frac{25812.8}{i} \Omega \quad (2.66)$$

Here, i can be a fractional (or an integer) values, at the same field minima are observed in R_{xx} (see Figure 1.1), h denotes Planck's constant and e is the charge of the electron. The longitudinal resistance

R_{xx} shows a peak at the transitions but it vanishes at the plateau values of R_{xy} . The existence of the fractional quantum Hall effect indicates that the Landau levels have internal structure.

The breaking of translational invariance is due to lattice impurities which contribute to the disorder of the system. Anderson localization phenomena in perpendicular magnetic fields depend on the range of the potential variations. Short-ranged disorder gives rise to strong scattering between the electrons whereas long-ranged disorder is usually associated with semi-classical images where orbits infiltrate throughout the system. What determines the type of disorder in quantum Hall samples is the range of the potential fluctuations relative to the magnetic length.

2.6.3 Shubnikov-de Haas oscillation

The Shubnikov de-Haas (SdH) oscillation is a quantum mechanical effect, which can be defined as an oscillatory change in resistivity. Thus, it is a typical example of solid-state quantum physics as oscillations in the resistivity exhibit the quantum nature of the electrons. When a magnetic field is applied in experiment, while maintaining the carrier density of 2DES constant, the energy of each Landau levels raises linearly with B with an increase of the Landau levels degeneracy at the same time. The chemical potential is pinned to the uppermost filled Landau levels until the degeneracy of the lower lying Landau levels is high enough to accommodate all charge carriers. At this point the chemical potential jumps and pinned to the next lower Landau levels. For a fixed charge carrier density n_s the density of states at the Fermi energy E_F and the resistivity are oscillating at a $1/B$ periodicity. Every time the chemical potential jumps, the electronic system undergoes a metal-insulator transition with zero conductivity. SdH oscillation amplitudes are sensitive to all scattering processes, including quantum scattering τ_q .

In typical SdH oscillation, two circumstances are mostly observed, first, the oscillations grow in amplitude as temperature is lowed and was theoretically derived by Ando as follows [33]:

$$\text{Amplitude} \propto \frac{\chi}{\sinh \chi} \quad (2.67)$$

Here, $\chi = \frac{14.7m^*T}{B}$ where T in Kelvin and B in Tesla. In other word, the thermal smearing coefficient, χ is proportional to the ratio $\chi = \frac{k_B T}{\hbar \omega_c}$. This is the expression for the temperature dependence of the oscillation amplitude and is valid as long as the oscillation amplitude is small. The thermal smearing indicates that cyclotron energy $\hbar \omega_c$ should be greater than the thermal energy $k_B T$ for oscillation to be observed, i.e. low temperatures are need. As shown in the previous sections, cyclotron resonance (CR) provides a more accurate and direct way to determine the effective mass of carriers. Conventionally, the effective mass is extracted from the temperature dependence of SdH oscillations. However, this is more complicated, because in contrast to CR, the position of SdH oscillations does not depend on the mass, but on the filling factors ($\nu = \frac{h n_s}{eB}$), which are independent of m^* .

In SdH oscillation, the effective mass m^* can be obtained from oscillation amplitude through the fitting procedures using equation (2.67). The other one is that the oscillation grows in amplitude as magnetic field increases. This occurs because scattering causes the Landau levels to have a finite energy width $\sim \frac{\hbar}{\tau_q}$. As B increases, $\hbar \omega_c$ will increase, so that the broadened Landau level become better resolved. Theoretical studies have shown that oscillation amplitude to varies with B as follows.

$$\text{Amplitude} \propto B^{-x} e^{-\frac{\pi}{\omega_c \tau_q}} \quad (2.68)$$

Here, x is a number which is approximated to one. Therefore, the scattering time can be obtained from the equation (2.61). In actual experiments there exist several scattering mechanisms depending on the sample structures and the source.

2.7 Band non-parabolicity

As discussed in section 2.3, band non-parabolicity appears on the band structures when there is large deviation from energy band. Equation 2.8 shows that, with increase of k , the effective mass

becomes heavier because the band energy deviates from the parabolic dispersion. This deviation from the parabolic energy dispersion is what is called non-parabolicity. In particular, the effective mass tends to increase with increasing energy. The effect of band non-parabolicity was evaluated in detail by Ando *et al.*, [34] using two band model approximation given as

$$m_c^* = m_b^* \left[1 + \frac{2K}{\varepsilon_g} (\mathcal{E}_F + \mathcal{E}_k) \right]. \quad (2.69)$$

Where, m_b^* is the band bare mass, E_g is the bandgap energy of semiconductors, E_F is the fermi energy given by

$$\mathcal{E}_F = \frac{\pi \hbar^2 n_s}{m_b^*}, \quad (2.70)$$

the average kinetic energy of the confined 2D electron gas in the z -direction is represented through $\mathcal{E}_K = \frac{\mathcal{E}_c}{3}$, when E_c is the confinement energy of the lowest of the subband measured from the bottom of the conduction band. Applying more accurate Fangi-Howard variational wave function gives;

$$\mathcal{E}_K = \frac{\hbar^2 b^2}{8m_b^*} \quad (2.71)$$

with

$$b^3 = \frac{48\pi m_b^* e^2}{\epsilon \hbar^2} \left(N_{dep} + \frac{11}{32n_s} \right). \quad (2.72)$$

The non-dimensional parameter K , represents band non-parabolicity. Equation 2.69 indicates that as the energy of carrier increases at a given bandgap energy, the increase of effective mass becomes evident. When magnetic field is applied, the term E_k is replaced by the quantized form $\left(N + \frac{1}{2}\right) \hbar \omega_c$ and the following equation is obtained

$$\frac{m_E^*}{m_b^*} = \left[1 + \frac{2K}{\varepsilon_g} \left(\left(N + \frac{1}{2}\right) \hbar \omega_c + E_k \right) \right]. \quad (2.73)$$

Here, N is the Landau index.

In 3D systems, the density of states diverges at $k_z = 0$, so that $E_k = 0$. However, in 2D electron system the non-parabolicity is larger than in the 3D case. This is due to formation of Landau levels in

the higher energy range as results of the sub-band energy. In the case of confined systems in the triangular potential, the value of E_K becomes a function of the electron density n_s depending on the location from the interface. In case of real band structures, for example in III-V, the valence bands are degenerate and the effect of other remote bands is important to take into consideration. Consequently, the two-band model is not essentially the best approximation to describe the conduction band. High-level model (three or five) taking account of the higher lying conduction bands is recommended, and appropriate value of parameter K is usually selected to account for the effects. In general, the parameter K is different depending on materials, and in the ideal two-band model, regardless of the materials $K = 1$. This approximation is performed by considering the conduction band minimum and the top valence band only, hence two-band model. Moreover, it is important to remember that the CR mass depends on the kinetic energy when dealing with the two-dimensional system. The high-level model was used in the CR study in GaN and GaAs 2DES, the value of $K = 2.5$ and 1.4 were obtained, respectively [14, 40].

2.8 Polaron effect

Semiconductor crystals such as II-VI and III-V are well known as polar semiconductors. This is because they have large electron-longitudinal-optical (LO) phonon interaction. In other words, in polar semiconductors the electron interacts strongly with the LO-phonon, and a large enhancement of the effective mass is expected through the resonant polaron effect in the vicinity of the LO-phonon energy.

Figure 2.13 shows the outlook of conduction electron in ionic crystal. The conduction electron together with its accompanying cloud is called a polaron. In polar semiconductors, the strength of electron-LO-phonon interaction is characterized by a non-dimensional coupling constant called the Fröhlich constant [41, 42],

$$\alpha = \frac{e^2}{\hbar} \left(\frac{m^*}{2\hbar\omega_L} \right)^{1/2} \left(\frac{1}{\epsilon_\infty} - \frac{1}{\epsilon_o} \right). \quad (2.74)$$

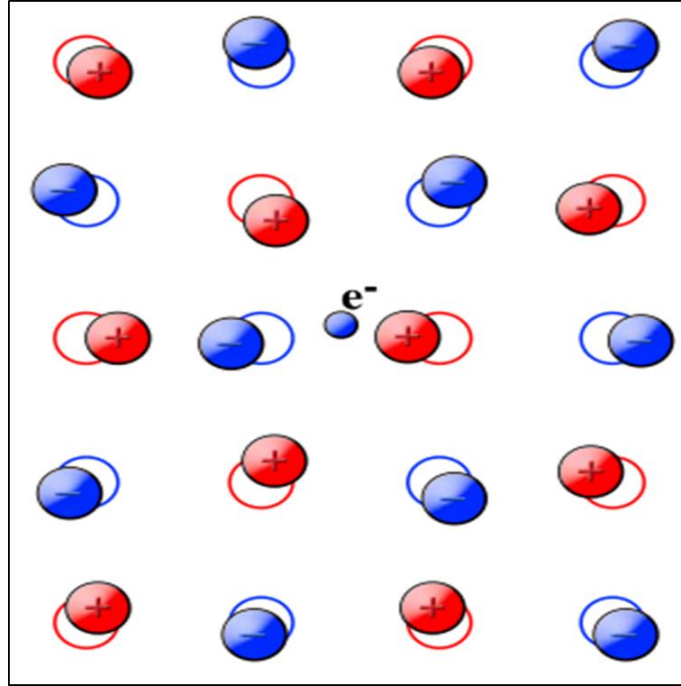


Figure 2.13 Conduction electron in ionic crystal [41].

Table 2.2 List of some of the polar semiconductors and their coupling constants.

Material	α	$\hbar\omega_L$ (meV)
GaAs	0.068	36.3
GaN	0.49	92
CdS	0.52	37.8
InN	0.22	86
InAs	0.052	29.6

Here, $\hbar\omega_L$ is the LO-phonon energy and ϵ_∞ and ϵ_0 are optical and static dielectric constants.

Table 2.2 shows the polaron coupling constant and $\hbar\omega_L$ for some of the polar semiconductors. The electron-LO-phonon interaction dominates the carrier scattering in polar semiconductors called LO-

phonon scattering.

As discussed in section 2.3, the effective mass of semiconductors is usually significantly larger than the band edge mass when measured in high magnetic fields. In high magnetic fields, the effective mass of electrons and holes are largely modified by the non-parabolicity of energy bands, in particular, in high carrier concentration regime. In polar semiconductors the effective mass which is measured by the CR is called polaron mass, which is usually larger than the bare mass by a factor of about $1 + \frac{\alpha}{6}$ [12, 41]. In a weak magnetic field regime, the bare mass corresponds to polaron mass m_p^* ,

$$m_p^* = m_b \left(1 + \frac{\alpha}{6}\right) \quad (2.75)$$

When CR energy $\hbar\omega_c$ approaches LO-phonon energy $\hbar\omega_L$ in high magnetic field, the interaction between electrons and LO-phonons resonantly increases and a large break takes place in the magnetic field dependence of the CR energy of the Landau levels. The effect of the large electron-LO phonon interaction near the resonance condition is called resonant polaron effect. The resonant polaron effect depends on the polaron coupling constant α , the applied magnetic field and effective mass of the semiconductors.

For semiconductors with lighter effective mass, the resonant effect can be readily observed even in relatively low magnetic field. However, in III-V semiconductors with heavier effective mass and larger phonon energy, higher magnetic fields are necessary to achieve resonant polaron effect. In II-VI compound semiconductors, α is significantly larger than in III-V compound (see Table 2.2), and the resonant polaron effect can be seen even at relatively low magnetic field regime.

In the magnetic field dependence of the CR energy, as $\hbar\omega_c$ approaches $\hbar\omega_L$, the effective mass becomes heavier, until the energy curve is flattened close $\hbar\omega_c = \hbar\omega_L$. At higher frequency range, there appears another branch, where the observed mass is smaller than polaron mass (see Figure 2.14 [41]). In the vicinity just above $\hbar\omega_L$ the observed mass becomes very small because of the resonant effect.

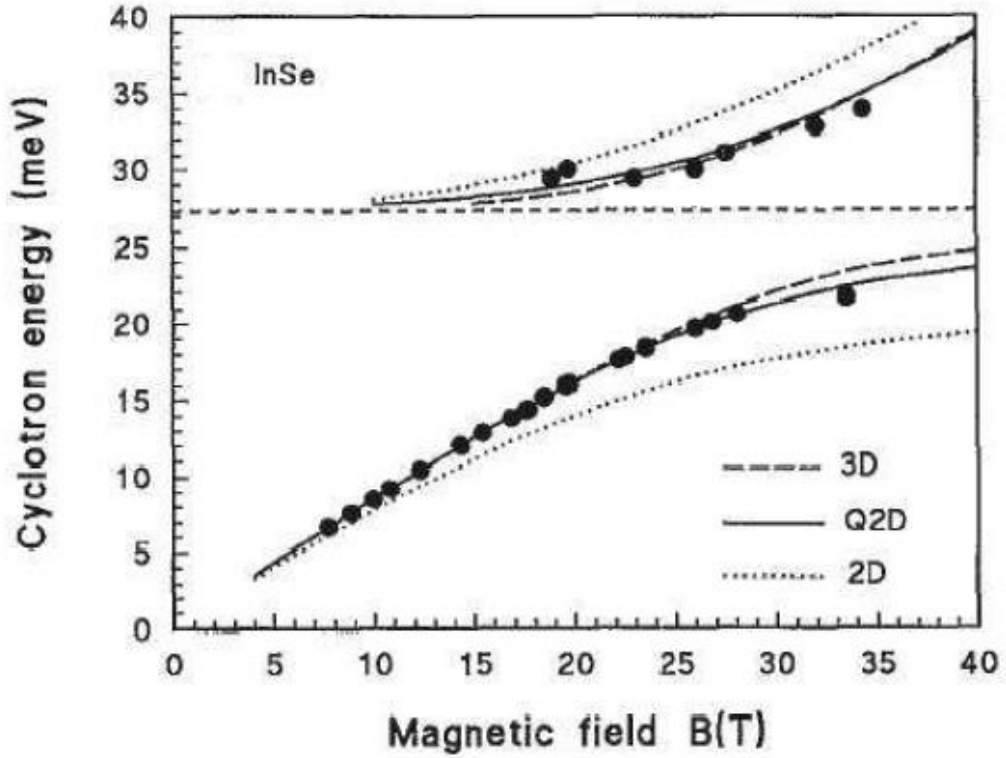


Figure 2.14 Magnetic field dependence of the cyclotron energy showing resonant position for InSe 2DES [41].

As the energy $\hbar\omega_c$ is further increased, the observed mass tends to approach the bare electron mass. The decrease of cyclotron mass when $\hbar\omega_c > \hbar\omega_L$ could be explained by considering the role of phonon cloud in the polaron effect. In semiconductor crystals, electrons are moving accompanying the phonon cloud. This is the main reason why the polaron mass is larger than the bare mass.

In two-dimensional electron systems, the polaron effect is different from the three-dimensional case because the electron-phonon interaction takes place in a space with different dimensions. According to Peeters *et al.*, the polaron mass (weak magnetic field limit) in 2DES is given by [43]

$$m_{2Dp}^* = \frac{m_b^*}{1 - \frac{\pi\alpha}{8} \left[1 + \frac{9(N+1)}{8} \left(\frac{\hbar\omega_c}{\hbar\omega_L} \right) + \dots \right]}, \quad (2.76)$$

where m_b^* is bare band mass and N corresponds to Landau index. And in the 3DES case,

$$m_{3Dp}^* = \frac{m_b^*}{1 - \frac{\alpha}{6} \left[1 + \frac{9(N+1)}{10} \left(\frac{\hbar\omega_c}{\hbar\omega_L} \right) + \dots \right]}. \quad (2.77)$$

These formulae can be applied only in the low-energy region far below the LO-phonon energy. Comparing equations (2.76) and (2.77), one may find that the polaron mass in 2DES is more than two times larger than in the 3DES case. In Figure 2.14, the theoretical curves show the results of calculations for coupling to the LO phonons in 3D systems, 2D system and after correction for the quasi-2D system using $\alpha = 0.29$. The agreement between theory and experiment is reasonable for the 3D case, but better for the quasi-2D system [41].

However, in 2DES screening effect by electrons is larger, hence, reduction of the polaron effect is expected. In a system with high electron concentration, the observed mass increases with increasing density. This is because the kinetic energy becomes larger as electron density increases. However, for materials with huge coupling constant even after screening effect the influence of polaron is not zero [11, 41-43].

2.9 Rashba effect

The spin angular momentum of electron can interact with its orbital angular momentum. This results into spin splitting of different energy levels which can lead to different transition energies. Such a behavior is known as spin-orbit interaction and their influence on the materials parameter is called Rashba effect. In 2DES formed at narrow-gap semiconductor often shows zero-field spin-splitting mainly due to spin-orbit interaction. This spin-splitting, transfers to Zeeman splitting energy, at higher fields through a certain transition process with or without of change of sign. The two-dimensional electron systems of InAs, and InGaAs heterostructures have the potential for application to spin field effect transistor because of large Rashba spin-orbit coupling along with high electron mobility [10, 11, 44]. In the zero magnetic field ($B = 0T$), the equation for spin-splitting energy with Rashba term can

be described as

$$\mathcal{E}(k) = \frac{\hbar^2 k^2}{2m^*} \pm \alpha_s k \quad (2.78)$$

Where α_s is a spin-orbit coupling constant for a given k vector in the direction of moving electron under the influence of Rashba term.

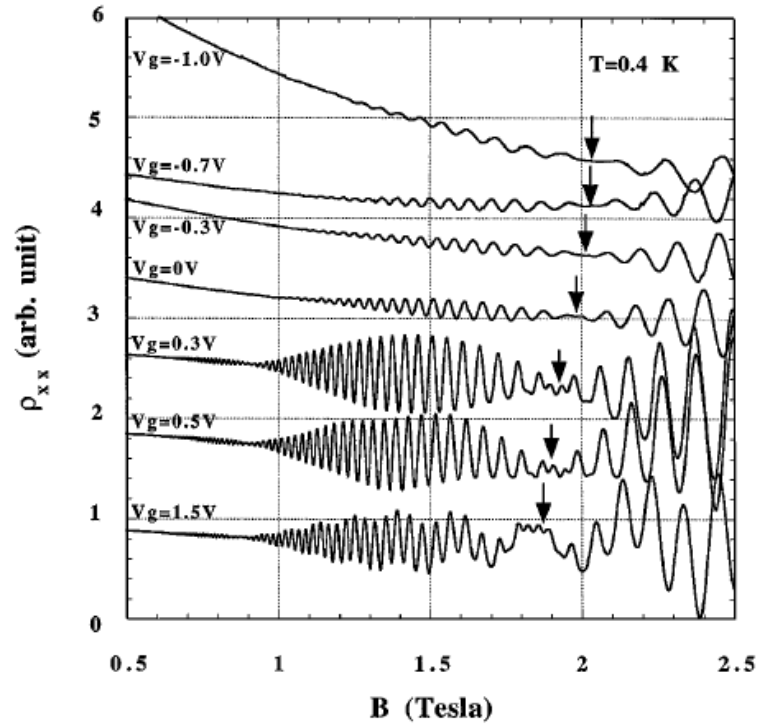


Figure 2.15 Voltage gate dependence of the Shubnikov–de Haas oscillations [11]

In semiconductor heterostructures, the Rashba spin orbit coupling is caused by structural inversion asymmetry which gives rise to spin precession. The spin-orbit coupling constant is an important factor to determine the Rashba effect in which moving electrons travelling in a perpendicular electric field undergo a Rashba effective magnetic field [9, 45]. The spin precession angle of electron spin can be controlled through the amount of Rashba magnetic field.

In a magnetic field B , transition energy between different spin levels (spin-up (+) and spin-down (-) electrons) can be described by [44].

$$\mathcal{E}_{\pm N} = \hbar\omega_c \left(N \pm \frac{1}{2} \sqrt{\left(1 - \frac{g^*m^*}{2m_0}\right)^2 + N \frac{\Delta_R^2}{E_F \hbar\omega_c}} \right) \quad (2.79)$$

and

$$\Delta_R^2 = \frac{8\alpha_s^2 m^* E_F}{\hbar^2} \quad (2.80)$$

where N is the Landau index (with $N \geq 1$), ω_c is the cyclotron energy, which is given by $\omega_c = \frac{eB}{m^*}$, and g is the effective g-factor. Δ_R and E_F are the zero-field spin splitting energy and the Fermi energy, respectively. For Landau index $N = 0$;

$$\mathcal{E}_0 = \hbar\omega_c \left(\frac{1}{2} - \frac{gm^*}{4m_0} \right) \quad (2.81)$$

Experimentally, spin-splitting effects in a heterostructure were studied through the beating patterns of the Shubnikov–de Haas (SdH) oscillations. Figure 2.15 shows Voltage gate dependence of the Shubnikov–de Haas oscillations. Using SdH method, Nitta *et al.* investigated the voltage gate dependence of the spin-orbit interaction using gated InGaAs/InAlAs heterostructures [11]. Similar studies were carried out on gate dependence of spin-orbit coupling constant of high indium content in an InGaAs/InAlAs heterojunctions by Sato *et al.*, and large coupling constant was obtained. The larger value of spin-orbit coupling constant was counted to the structure-dependent so-called interface contribution in the Rashba term [46].

On the other hand, although, CR is the most accurate method for the direct observation of the spin splitting energy, there are a few CR reports, so far [44, 47]. Many of these reports were limited to low magnetic field regime because it is well known that at high magnetic field region, the Zeeman energy becomes dominant rather than Rashba spin splitting energy. Therefore, in order to clearly observed spin orbit coupling, low magnetic field is a pre-requisite. However, at low magnetic field the CR energy transition between the landau levels deviates from the linear dependence of the magnetic

field. Such anomalous magnetic field dependence was observed by Imanaka *et al* [44] in their attempt to investigate magnetic field dependence of the CR in a high indium concentration, InGaAs/InAlAs inverted heterostructure at a millimeter wave range (see Figure 2.16). Furthermore, the energy of Landau levels becomes linear dependence of the magnetic field when small Rashba spin splitting occurs. Such kind of estimation was done by Fujii *et al* [47], in their effort to determine the zero-field spin splitting by means of FIR magneto-optical absorption measurements at low magnetic fields up to 6T only. However, so far, there are no reports on the CR of InGaAs/InAlAs heterostructures measured

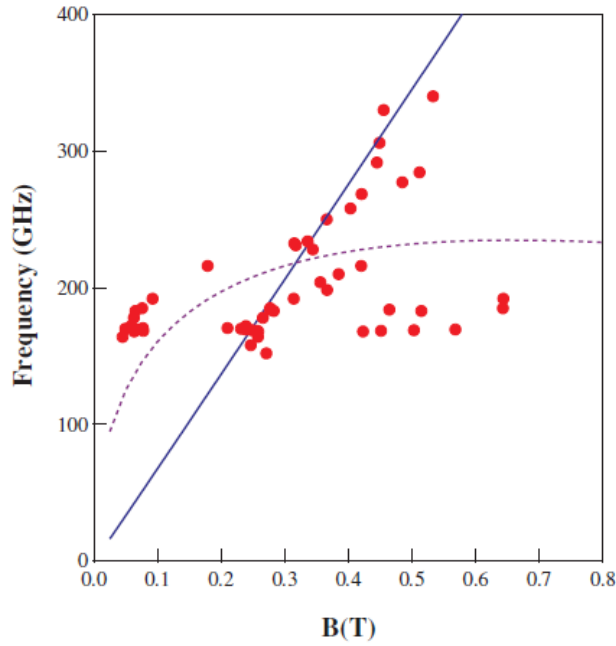


Figure 2.16 Magnetic field dependence of the CR energy for InGaAs/InAlAs heterostructures measured with millimeter-wave vector network analyzer. The dashed curve shows calculated result of the transition energy between different spin levels using equation (2.79) [44].

in the terahertz region. Moreover, it was recommended that further experimental confirmation and theoretical support are needed to clarify the CR spectra at the wide energy range [44, 47].

2.10 Plasmon

In metallic material, a plasma oscillation is regarded as a collective longitudinal excitation of the conduction electron. In other word, plasmon is a quantum of plasma oscillation. It is possible to excite a plasmon by passing an electron through a thin metallic film. The charge of the electron couples with the electrostatic field fluctuations of the plasma oscillations. The transmitted electron will show an energy loss equals to integral multiples of the plasmon energy.

The dielectric function $\varepsilon(\omega, \mathbf{K})$ of the electron gas, with its strong dependence on the frequency and wave vector has significant consequences for the physical properties of solids. In some case, $\varepsilon(\omega, 0)$ explains the collective excitations of the Fermi volume and surface plasmons. In another circumstance, $\varepsilon(0, \mathbf{K})$ describes the electrostatic screening of the electron-electron, electron-lattice and electron-impurity interaction in crystals. The dielectric constant ε of the electrostatics is defined in terms of the electric field $\mathbf{E}$ and polarization $\mathbf{P}$, and the dipole moment density is given as

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} = \varepsilon \varepsilon_0 \mathbf{E} \quad (2.82)$$

where ε is also known as relative permittivity.

For plasma optics, the long wavelength dielectric response $\varepsilon(\omega)$ of an electron gas is obtained from the equation of motion of a free electron in an electric field;

$$m \frac{d^2 x}{dt^2} = -eE \quad (2.83)$$

If x and E have the time dependence $e^{-i\omega t}$, then

$$-\omega^2 m x = -eE; \quad x = \frac{eE}{m\omega^2}. \quad (2.84)$$

The dipole moment of one electron is $-ex = -\frac{e^2 E}{m\omega^2}$, and the polarization, defined as the dipole moment per unit volume, is

$$\mathbf{P} = -n_s ex = -\frac{n_s e^2 E}{m\omega^2} \quad (2.85)$$

Here, n_s is the electron density.

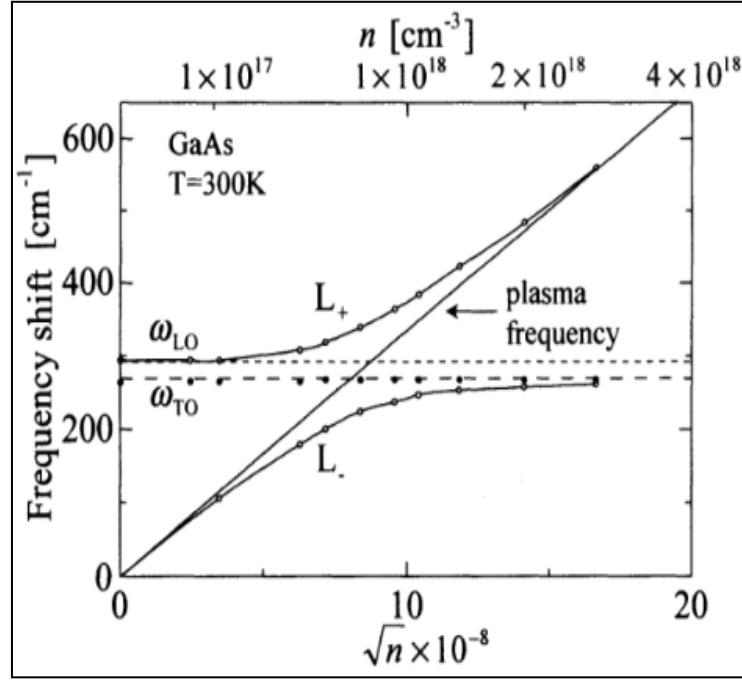


Figure 2.17 Carrier concentration dependence of the frequency for GaAs at room temperature. L+ and L- are the plasmons coupled to LO-phonons [31]

The dielectric function at frequency ω is

$$\varepsilon(\omega) = \frac{D(\omega)}{\varepsilon_0 E(\omega)} = 1 + \frac{P(\omega)}{\varepsilon_0 E(\omega)}. \quad (2.86)$$

The dielectric function of the free electron gas is obtained using eqns (2.85) and (2.86) as

$$\varepsilon(\omega) = 1 - \frac{n_s e^2}{\varepsilon_0 m \omega^2}. \quad (2.87)$$

The plasma frequency ω_p is defined by the relation

$$\omega_p = \sqrt{\frac{n_s e^2}{\varepsilon_0 m}}. \quad (2.88)$$

Therefore, plasma can be defined as a medium with equal concentration of negative and positive charges, of which at least one charge has to be mobile.

In crystals the positive charges are balanced with negative charges of the conduction electrons.

Hence the dielectric function (2.88) can be written as

$$\varepsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}. \quad (2.89)$$

Figure 2.17 shows experimental and calculation results in GaAs at room, where TO-phonon do not couple with plasmon, but LO-phonon couples with the plasmon and split into two branches (L+ and L-) [31]. As shown in equation (2.88), the plasma frequency is proportional to the square root of the carrier concentration, and with changing carrier concentration plasma frequency can couple with LO-phonon frequency. This is because plasma frequency and LO-phonon frequency are both longitudinal but not TO-phonon frequency. Such a coupled mode of plasma frequency and LO-phonon is called plasmon-LO phonon coupled mode which was predicted theoretically and prove experimentally proved [31]. The coupled modes can be presented by the following;

$$\omega_{L\pm}^2 = \frac{1}{2} \left((\omega_p^2 + \omega_{LO}^2) \pm \sqrt{(\omega_p^2 + \omega_{LO}^2)^2 - 4\omega_p^2\omega_{TO}^2} \right). \quad (2.90)$$

Where ω_{L+} and ω_{L-} are the resonance frequency of the plasmon-LO phonon coupled mode, above and below the LO-phonon frequency (in Figure 2.17, it is denoted as L+ and L-). ω_{LO} and ω_{TO} stands for longitudinal-optical phonon and transverse-optical phonon, respectively [31].

CHAPTER THREE

Samples and Experiments

3.1 Growth techniques

As discussed in the previous chapter, samples under study were grown by two growth techniques, namely, the metal organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). The GaN and InGaN were grown by MOCVD in NIMS, and InGaAs was grown by MBE at the Japan Advanced Institute of Science and Technology (JAIST). Seven types of heterostructure samples were studied in this research work namely; three series of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ samples with different carrier concentration (Sample A, Sample B and sample C), three series of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{In}_x\text{Ga}_{1-x}\text{N}$ samples with different indium composition ($x = 4.1\%$, 5.0% and 6.8%), inverted $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ single-heterostructures. All the samples were designed to produce high electron mobility suitable for studying cyclotron resonance measurements.

Before detailed description for each sample, first, a brief introduction of widely used techniques for growing epitaxial layers of semiconductors (MBE and MOCVD) are given as follows. Figure 3.1 shows the main components of a standard MBE system. An MBE machine is very precise among the epitaxial growth techniques. The machine consists of stainless still vessel with diameter around 1 m kept under ultrahigh vacuum (10^{-11} mbar) by series of pumps. This means that, the whole chamber must be very well evacuated to prevent contaminations entering the layers. The constituent materials which makes up the semiconductors to be grown evaporates from the effusion cells at a rate controlled by the cell temperature. The cells are also utilized for doping process. Evaporated atoms form a beam which is accelerated by pressure differential at the orifice towards the substrate. The evaporation rate is set such that about one monolayer is deposited per second. The composition of the layers is controlled by shutters which is located inside of each cell. The substrate is usually mount on a holder with a precise temperature to ensure that the deposited atoms are dynamic to allow spread out over the

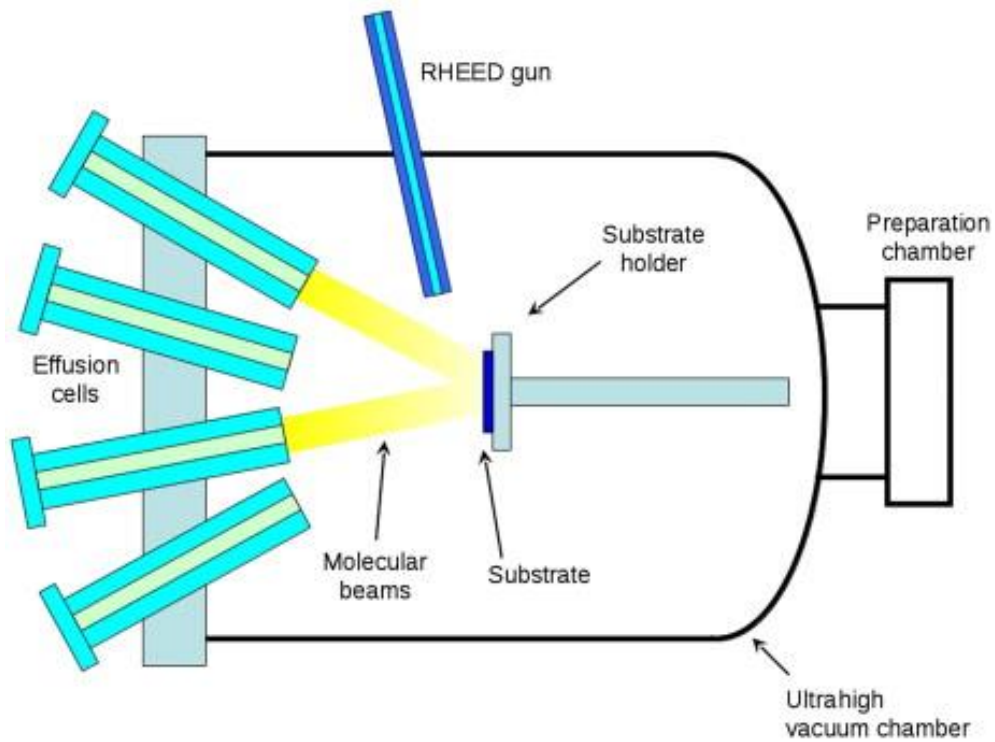
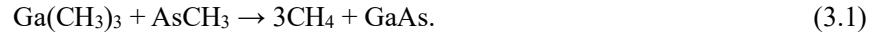


Figure 3.1 Schematic of a typical molecular beam epitaxy (MBE) system [48].

substrate in monolayers instead of creating clusters. Reflection High Energy Electron Diffraction (RHEED) gun is included in the system for on-site monitoring of the sample during growing [48].

Figure 3.2 shows the main parts of a MOCVD system [49], which is one of the commonly process used for growing high-quality semiconductor multilayers, recently. In MOCVD machine, the ingredients of the semiconductor to be grown is transported through the stream tube to the substrate as gaseous precursors formed through the reacting elements with organic radicals. After that, the precursors are allowed to move along in a stream of hydrogen. The substrate is located in a chamber which is heated by the radiofrequency coil. The reaction of precursors takes place near the hot substrate. Thus, the desired semiconductor is deposited on the substrate. A typical reaction for growth of GaAs heterostructures, for example, is given as;



The inclusion of fast solenoid valves enables the source of the various components to be switched on and off rapidly. In this work, the GaN and InGaN heterostructures samples were grown by MOCVD.

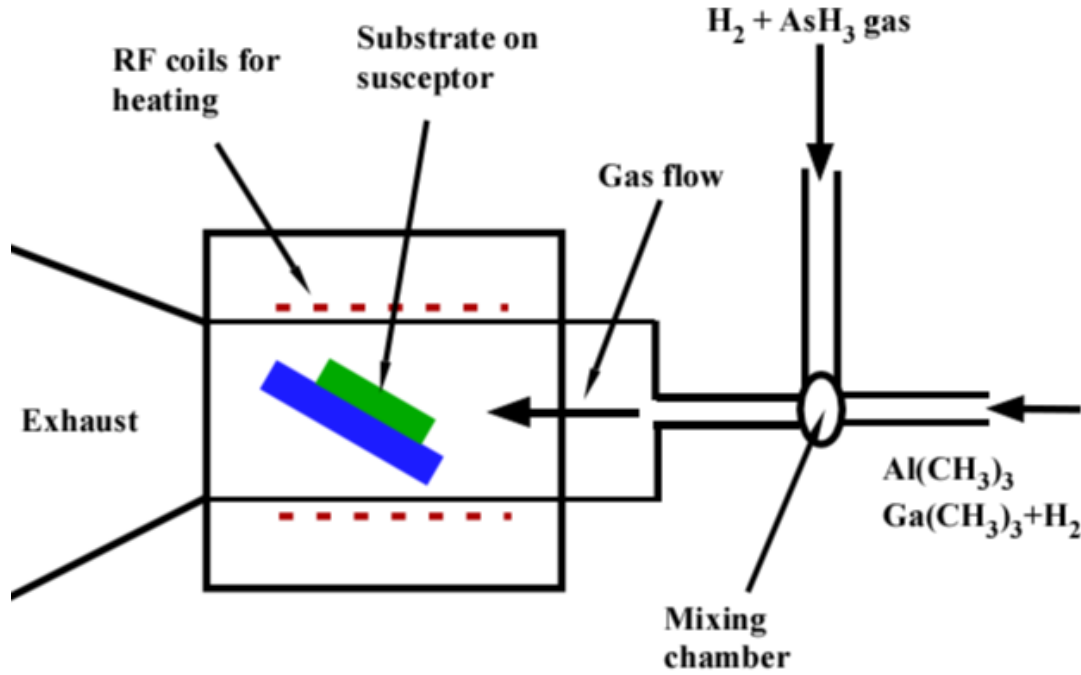


Figure 3.2 Schematic of an MOCVD system

To conclude on this part, MOCVD is a chemical process whilst MBE is a physical process. As discussed above, in MOCVD reactant gases are fed into the system at high pressure ~ 1 Torr whereas in MBE ultra-high vacuum conditions (10^{-8} Torr) are required for deposition. Moreover, MBE is very complicated, slow and expensive technique while MOCVD is a high-speed technique, preferred for large scale production and considered as highly flexible able to deposit semiconductors. In the following section, the details for each sample which were obtained from the above methods are given. It is important to note here that, detailed growth mechanism is beyond the scope of this work.

3.1.1 AlGaN/InGaN and AlGaN/GaN heterostructures

Figure 3.3 shows the outlook for $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructure. The $\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructure samples ($x = 4 \sim 7\%$) were grown on special AlN template/sapphire (SCIOCS Co. Ltd.) using MOCVD techniques. The AlN template fabricated by hydride vapor phase epitaxy on sapphire substrate was used in order to improve the quality of InGaN in relation to crystalline quality and alloy scattering. Tri-methyl gallium, Ammonia, tri-methyl aluminium, and tri-methyl indium were used as the Ga, In, Al, and N precursors. During the growth process of InGaN, the AlN template was introduced into MOCVD machine, followed by annealing process in hydrogen (8 slm), nitrogen (2 slm) and ammonia (10 slm) gas flows under atmospheric pressure. The growth temperatures were ramped from room temperature to 930°C for nine minutes.

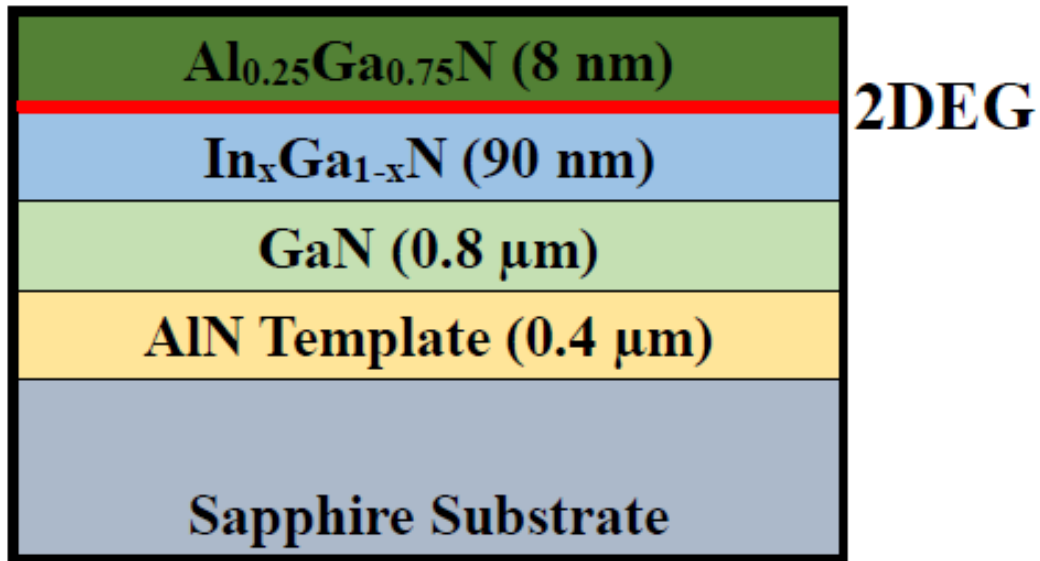


Figure 3.3 Sketch of the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructure showing 2DES at the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{In}_x\text{Ga}_{1-x}\text{N}$ interface. The indium concentration is, $x = 4.1\%$, 5.0% and 6.8% .

The system was allowed to stabilize the growth temperature at 930°C for two minutes, then, tri-

methyl gallium was supplied into the reactor to deposit a GaN film directly on the AlN template without using a low temperature buffer layer. GaN layer was deposited for twenty minutes and the typical thickness was obtained as 0.84 μm equivalent to a growth rate of 2.5 $\mu\text{m}/\text{h}$. The substrate temperature was then reduced and the ambient in the reactor was exchanged from hydrogen to nitrogen gas for the growth of InGaN film. Through supplying tri-methyl indium, InGaN films were grown at different times up 3600 seconds at a growth rate of 0.54 $\mu\text{m}/\text{h}$. By applying the same growth procedures, three samples of InGaN with mole fraction of 4.1%, 5.0% and 6.8% were successful deposited at 790, 770 and 740 $^{\circ}\text{C}$ respectively. A barrier layer of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}$ of 8 nm thickness was grown on the InGaN layer at the same temperature by supplying tri-methyl aluminum soon after deposition of the tri-methyl indium. The deposition time for the AlGaIn was 90 seconds equivalent to 8 nm of thickness. The lattice constant in the a- and c-plane was estimated to be 3.099 $\text{\AA}$ and 4.990 $\text{\AA}$, respectively.

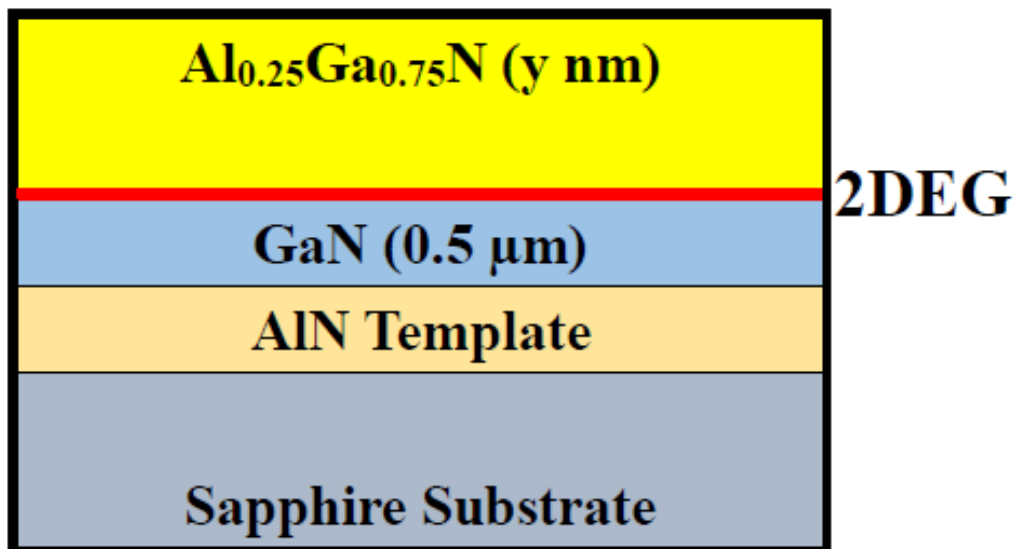


Figure 3.4 Schematic layered structure of $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ sample. The barrier layer thickness $y =$ 15 nm, 30 nm and 60 nm for sample A, B and C, respectively.

The structural properties of the samples were investigated as following; the degree of alloy scattering in InGaN was evaluated by Urbach energy determined by photothermal deflection spectroscopy. The root mean square surface roughness of the AlN templates was observed as 2.8 nm from the atomic force microscopy. Moreover, by using x-ray diffraction the InN mole fraction was evaluated as shown above. As indicated in chapter four and five, magneto-transport experiments were performed in order to check the sample quality.

The $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure samples were also grown by MOCVD on sapphire substrate with AlN template (fabricated by Dr. Sumiya). Figure 3.4 shows the sample structure for the $\text{Al}_{0.25}\text{Ga}_{0.75}\text{N}/\text{GaN}$ heterostructure. For $\text{Al}_{0.25}\text{GaN}/\text{GaN}$ samples, the carrier concentration and mobility were controlled through the barrier layer thicknesses. The thickness of GaN layer was 0.5 μm for all GaN samples.

3.1.2 InGaAs/InAlAs heterostructures

An $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ inverted heterostructure sample was grown on a semi-insulating GaAs substrate by the MBE method. The $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ sample was fabricated from one wafer, which has a wide (80 nm) well (channel) on the top surface of a undoped (20 nm) $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ barrier and a thin (10 nm) $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ cap layer. Schematic layer structure is shown in Figure 3.5. The $\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ step-graded-buffer was adopted to expand the lattice constant by utilizing metamorphic MBE growth. Although the $\text{In}_{0.75}\text{Al}_{0.25}\text{As}/\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ material system is not so widely studied, detailed growth recipes have been well known and are made open by different groups including the grower of this sample [50].

In this sample modulation doping technique was performed. The Si-doping sheet is situated between InAlAs (20 nm) and InAlAs (40 nm), which is almost 20 nm away from the $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ interface, as shown in Figure 3.5. The electrons, supplied by the Si-doping

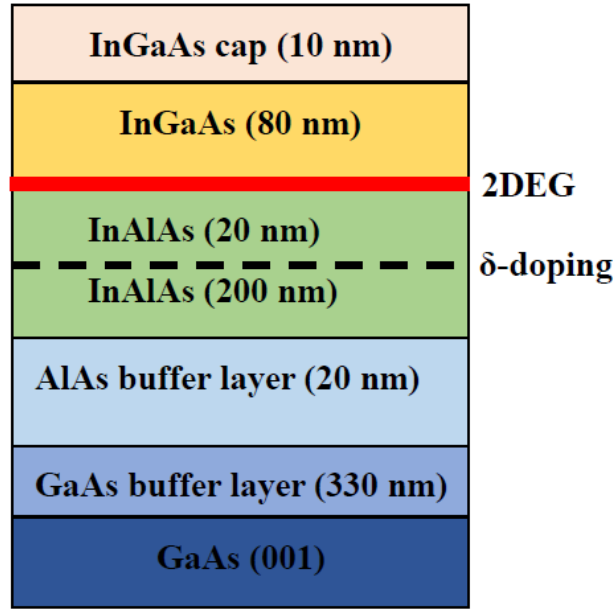
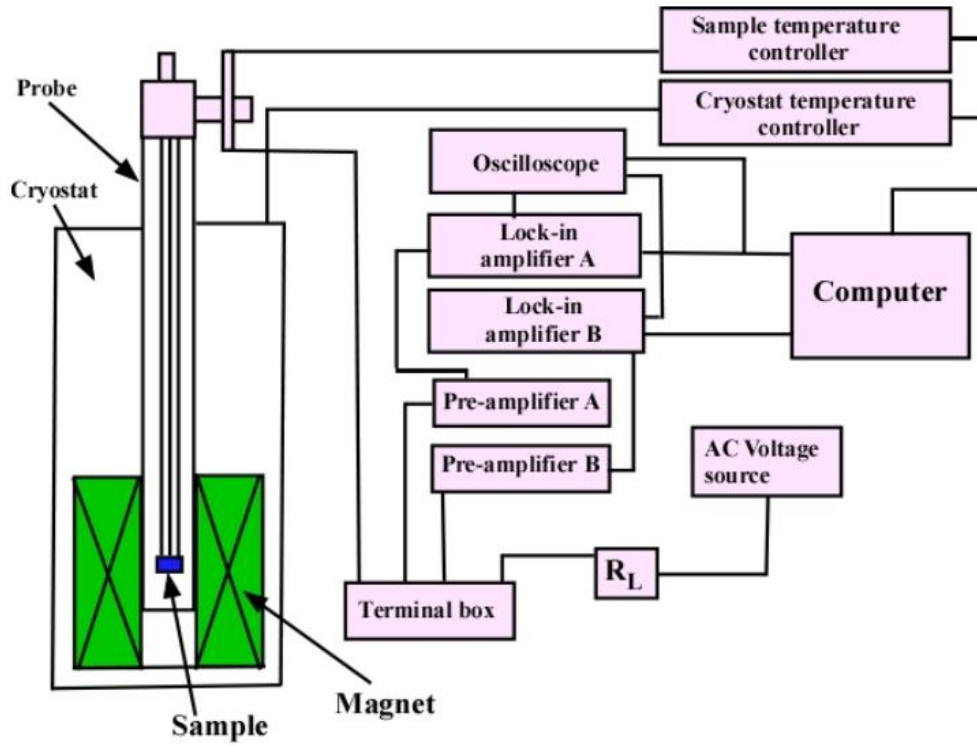


Figure 3.5 A schematic cross section of modulation doped $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ structures grown on GaAs substrate by MBE.

sheet, tunnel to the energetically favorable InGaAs region. The charge redistribution creates a potential notch near the interface, where the electrons are trapped. Thus, the trapped electron creates the 2DES characterized by high mobility. Essentially this high mobility 2DES makes the sample a suitable choice to study cyclotron resonance.

3.2 Magneto-transport measurements

As discussed in the previous chapters, magneto-transport measurement is one of the important experiments for understanding electronic transport properties in materials. In the actual magneto-transport measurements, one needs a Hall bar sample structure. However, in the absence of Hall bar sample, four terminal, six terminal or van der Pauw techniques can be employed for characterization of semiconductors. In this work, the four and six terminal techniques were used in order to check the sample quality, and to estimate the effective mass through temperature dependence of the SdH



(a)



(b)

Figure 3.6 (a) Schematic and (b) Outlook of experimental set up for magneto-transport measurements.

oscillation. In four terminal, Hall resistance and magneto-resistance are measured separately. Figure 3.6 shows experimental set up for magneto-transport measurements used in this research work. The transport measurements were carried out using a standard lock-in amplifier technique. Both magneto-resistance and Hall-resistance were measured simultaneously using two lock-in amplifiers and two low-noise pre-amplifiers (see Figure 3.6).

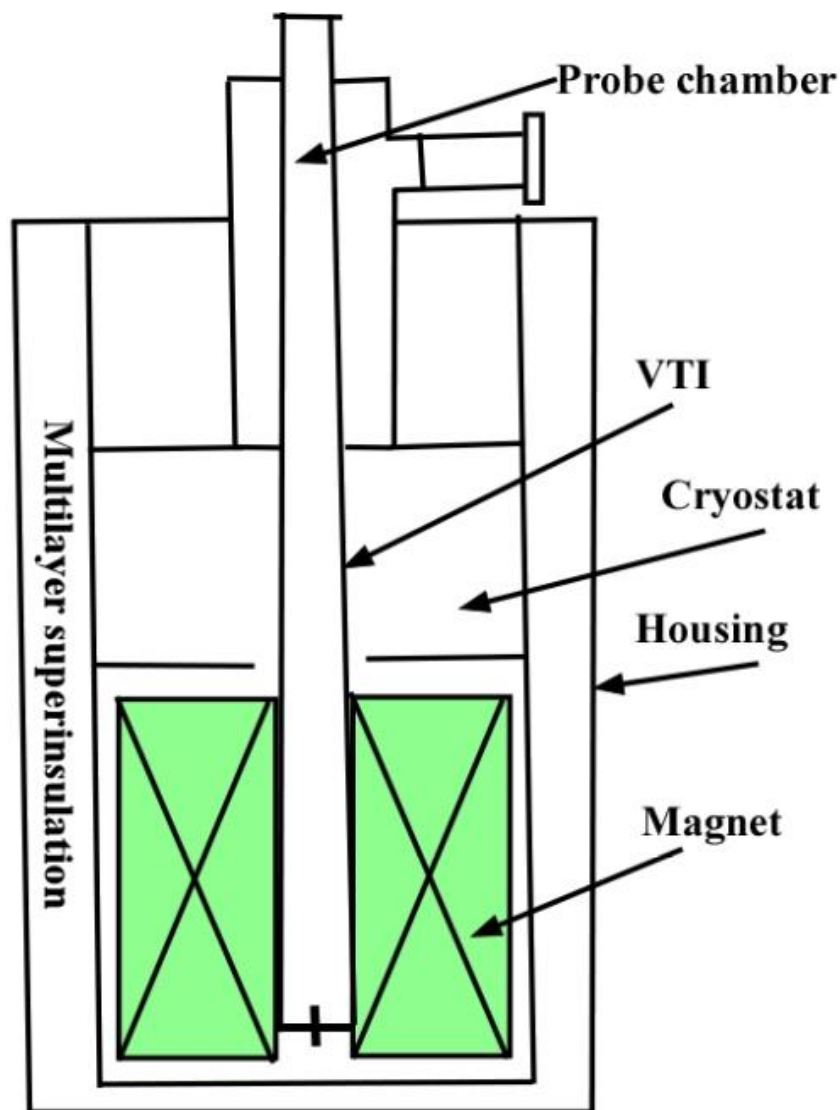


Figure 3.7 Schematic diagram of 15 T superconducting magnet used in this work.

In this work, 15T superconducting magnet was used for both cyclotron resonance and magneto transport measurements. Figure 3.7 shows the schematic diagram of 15T superconducting magnet (Max. current 133A, Voltage 4.8V). The superconducting magnet consists of cryostat and variable temperature insert (VTI). The needle valve is used for controlling the flow of cold helium gas inside the VTI. Through controlling the flow of cold helium gas in the VTI it possible to realize low temperature down to 1.7 K around the sample. The temperature controller is connected directly to the temperature sensor located in the VTI for controlling and monitoring the VTI temperature. Two temperature controllers were used for monitoring the sample and cryostat temperature (see Figure 3.8).



(a)



(b)

Figure 3.8 The outlook of experimental equipment (a) Sample and cryostat temperature controllers (b) Liquid helium pumping systems used in this work.

A second temperature controller is connected directly to the measuring probe with temperature

sensor located around the sample. This is used for monitoring the sample temperature during the experiments. Power supply system is used for controlling the amount of power required and for setting magnetic field to be applied to the sample. The power supply system is also used for monitoring and controlling the sweeping rate. The magnet has many sensors for safety monitoring and protection from quenching. During experiments the sample is inserted in the probe and placed at the center of magnet in such a way that the field is applied perpendicular to the two-dimensional electron system.

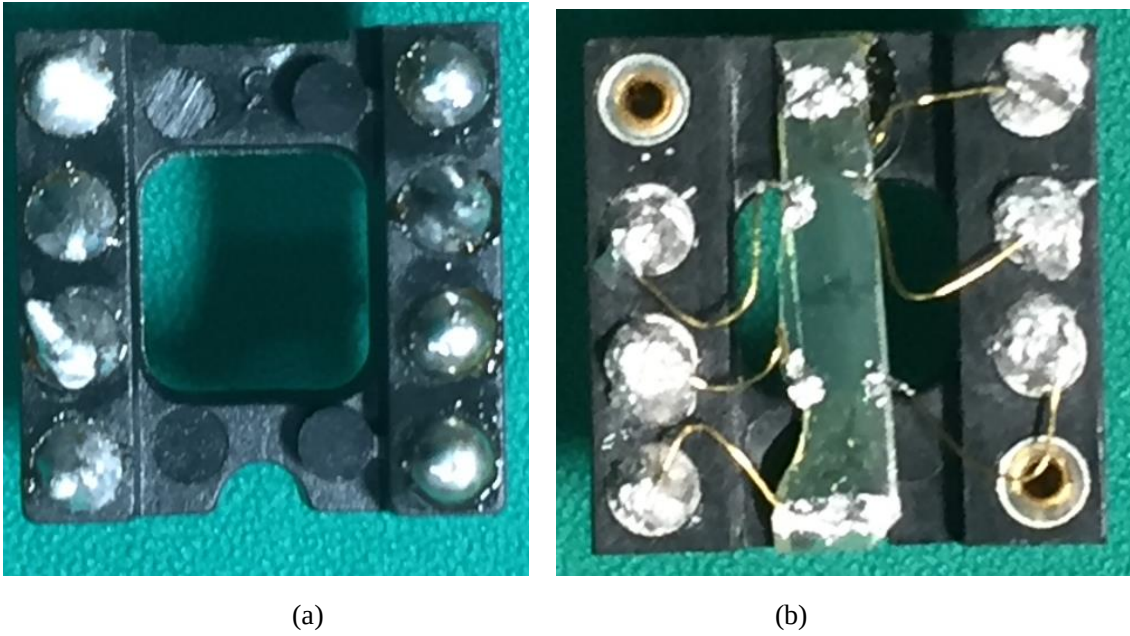


Figure 3.9 The outlook of sample holder (a) without the sample (b) with inserted sample. Gold wires were used for wiring the contacts.

An oscilloscope was used for onsite monitoring of signals to noise ratio. The AC voltage source of $V = 1$ V (supplied by lock-in amplifier) was wired in series with a large load resistance source, $1\text{M}\Omega$. Hence, a low current, $1\mu\text{A}$ was applied through the samples. Through this procedure, heating effect in the sample was avoided while ensuring linear response. The sample temperature sensor (CERNOX)

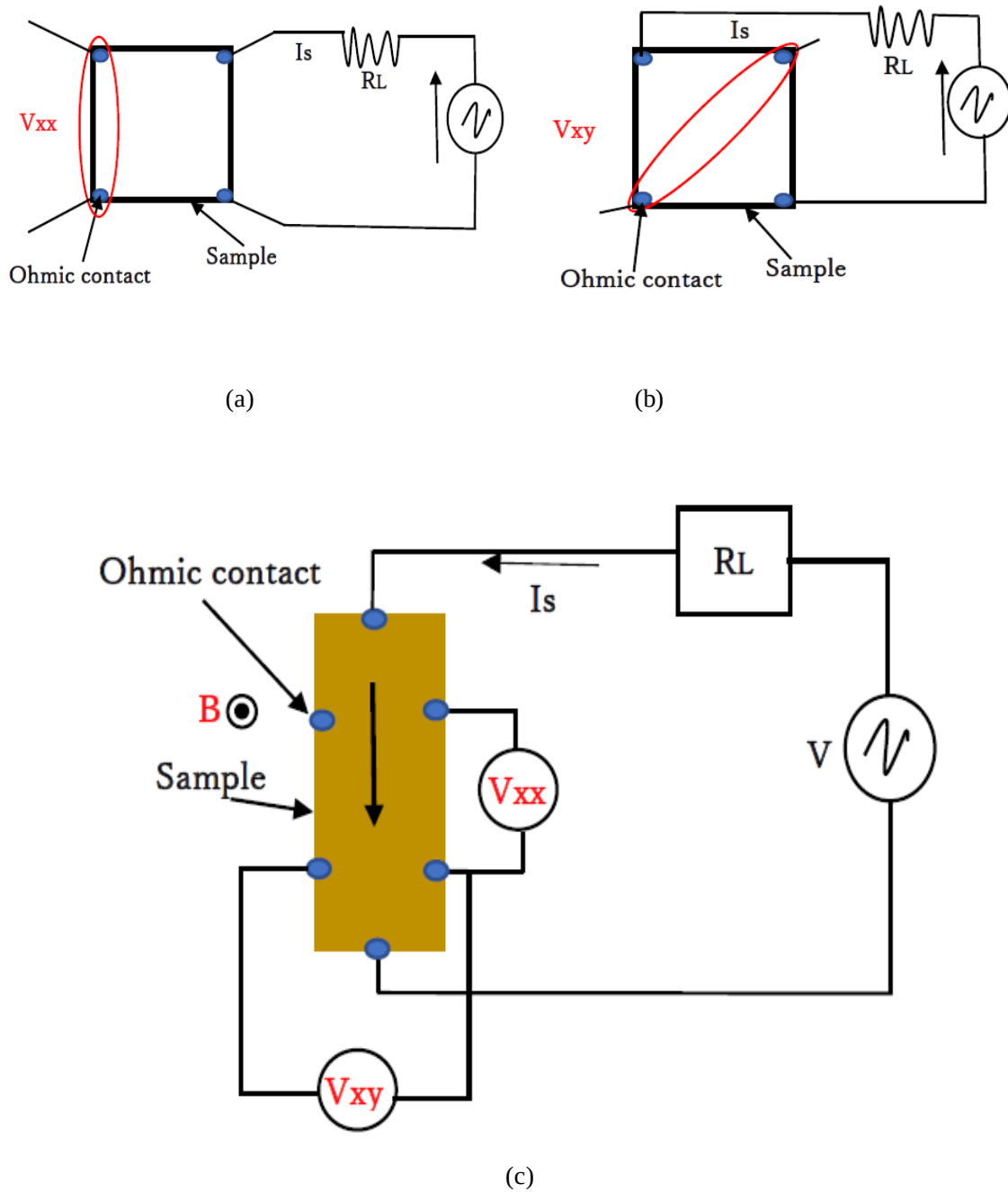


Figure 3.10 Typical arrangements for magneto-transport measurement (a) longitudinal voltage (V_{xx}) was measured parallel to the current direction and (b) Hall voltage (V_{xy}) was measured perpendicular to the current direction, (c) Six terminal arrangement, both longitudinal voltage and Hall voltage are measured simultaneously. Magnetic field B was applied perpendicular to the sample.

located close to the sample in the measurement probe was used for monitoring the sample temperature.

Figure 3.9 shows typical sample holder without the sample and with inserted sample. The gold wires were used for connecting ohmic contact and the sample holder. Prior to the measurements, the samples were first cleaved into suitable shape using a cleaving machine. In order to attach current and voltage leads, the ohmic contacts were fabricated on these samples using pure indium. The gold wires were used for wiring the sample-contacts to the sample holder-contacts. As introduced earlier, four terminal method was used for GaN samples, and six terminal method was used for InGaN and InGaAs samples. Figure 3.10 shows the typical four terminal contacts for AlGaIn/GaN samples.

The samples (AlGaIn/GaN and AlGaIn/InGaIn) were inserted into the superconducting magnet using a hand-made-probe for magneto-transport measurement. The measuring probe was connected directly to the sample temperature controller using electric cable. A 15 T superconducting magnet with a variable temperature insert (VTI) was used. The experimental temperature was kept down to $T = 1.7$ K and was monitored by using temperature controllers. The sweeping rate of magnetic field was set to be 0.0633 T/min. In the case of InGaAs/InAlAs sample, magneto-transport measurements were carried out using hybrid magnet up to 27 T. The hybrid magnet consisted of superconducting magnet and resistive magnet which can generate magnetic field up to 45T. Six terminal method was used for measurement of InGaAs sample. Hence both magneto-resistance (R_{xx}) and the Hall resistance (R_{xy}) were simultaneously measured.

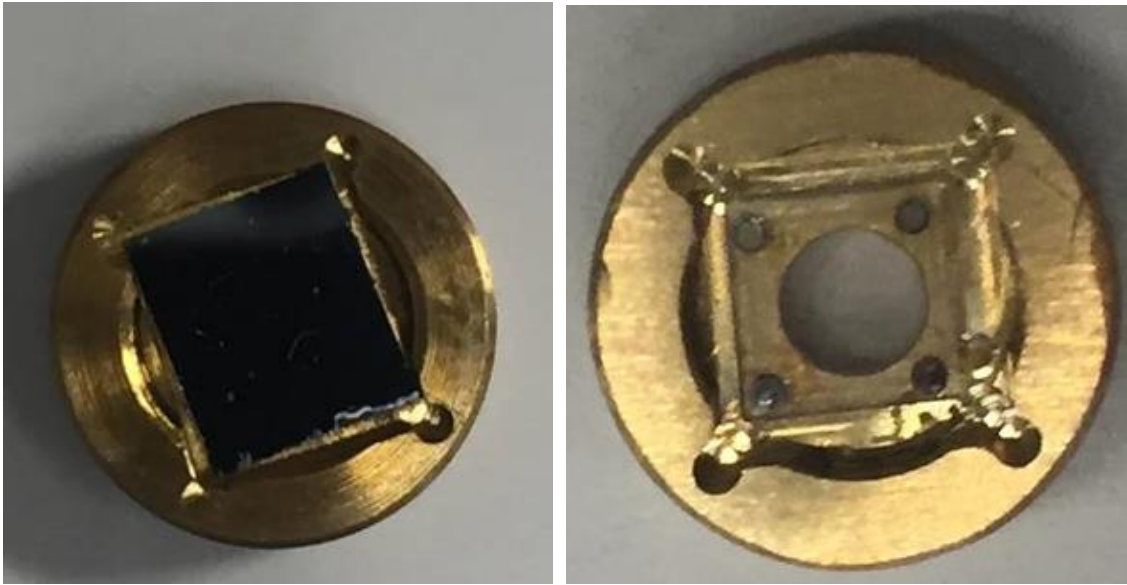
3.3 Cyclotron resonance measurements

Cyclotron resonance (CR) experiment is a direct measurement of ω_c using far-infrared wave or millimeter-wave to excite transitions between Landau levels. In chapter two, detailed discussion on CR theory has been provided. In this section, CR experiment set up and its main equipment/components used are presented. In this research, CR experiments were performed at low

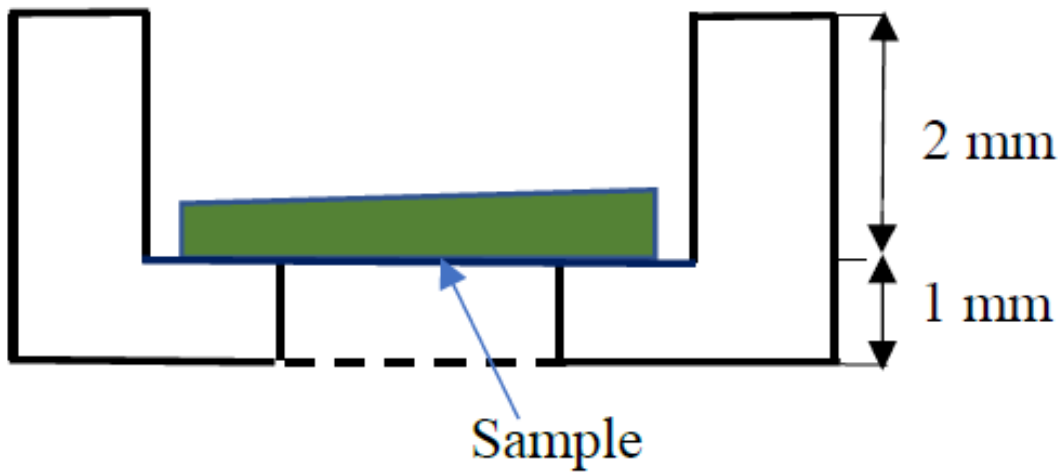
temperature (1.7 K) using a Fourier transform spectrometer (Bruker-Vertex 80v) in combination with superconducting magnet up to 15 T. The magnetic fields were applied perpendicular to the 2DES for each sample (Faraday configuration). The transmitted light through the sample was detected using helium cooled bolometer. In the following sections, a brief overview on the main components/equipment (Fourier transform spectrometer, superconducting magnet and bolometer) and their supporting components used for CR experiments are presented. First, sample preparation for CR measurements will be provided in the following section.

3.3.1 Sample preparation for CR measurements

Figure 3.11 shows the outlook and schematic diagram of sample holder with sample inside. Before taking CR experiments, the samples were cleaved using cleaving machine to obtain appropriate dimension for effective and efficiency wave transmission. The typical dimension of the present samples is estimated to be $5 \times 5 \times 0.5 \text{ mm}^3$ which can be accurately fixed into the sample holder to avoid transmission leakage (see Figure 3.11 (a)). The backside of the samples was wedged and polished using wedging block and lapping film, in order to avoid interference effects of the probe light (see Figure 3.11(b)). The sample were fixed into a sample holder using low temperature glue. The sample holder was fixed into the hand-made probe. For accurate monitoring of sample temperatures, sample was fixed in such as a way that it is close enough with the temperature sensor. The probe was finally inserted in the magnet in such a way that the sample is at the center of the magnet. The probe was connected directly to both spectrometer and bolometer using hand-made light pipes.



(a)



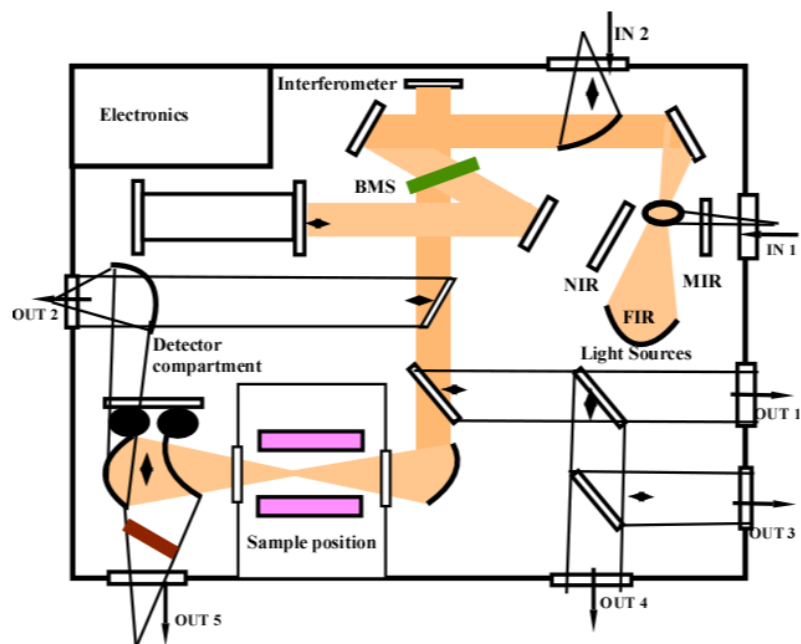
(b)

Figure 3.11 (a) The outlook of samples in the sample's holder (b) schematic diagram of sample holder with wedged sample at the backside. The sample is inserted at the center of the sample holder-hole in such a way that maximum transmission is archived.

3.3.2 Fourier transform spectrometer

Figure 3.12 shows a Fourier-Transform (FT) spectrometer, Bruker-Vertex 80v model used in this research work. FT spectroscopy can be employed for a long range of frequencies varying over ultraviolet, visible, near infrared, mid infrared and even far infrared regions by selecting different beam splitters and detectors for the required ranges. No other dispersive technique can be used for such a wide range of frequencies [51].

The FTIR-spectrometer consists of a detector which can be changed depending on the experimental requirement. There are several kinds of detectors which include; bolometer for FIR detection, MCT (HgCdTe) for medium infrared (MIR), and indium antimonide (InSb) for near infrared (NIR) measurement range. Secondly, a light source with optional radiation source such as mercury lamp for FIR, globar for MIR and halogen for NIR. Thirdly, an interferometer for which spectral encoding of the incoming beam takes place before the resulting interferogram signal is transmitted through the sample. The mercury lamp was used as a source for emitting broadband infrared light. The radiation is coupled in the interferometer where a beam splitter (BMS) (could be Mylar or potassium bromine) divides it into two beams. The first beam is directed to a fixed mirror and is reflected. The second beam is directed to a moveable mirror and is also reflected. Subsequently both beams reach the beam splitter again where they are recombined. Depending on the frequencies and the position of the movable mirror the two beams are interfering, because of the different interfering it is possible to compare each mirror position with a certain wavelength and consequently wavenumber. The recombined beam passes the sample and reaches the detector. The measured signal is called interferogram and represents the intensity of the IR-radiation in dependency of the mirror position and the absorbance of the sample. The computer controls optical components, collects and stores data, carries out calculations on data, and displays spectra after performing a Fourier transform of the interferogram.



(a)



(b)

Figure 3.12 (a) Typical Fourier transform spectrometer showing optical path (b) Outlook of spectrometer (Bruker-Vertex 80v model) used in the present work

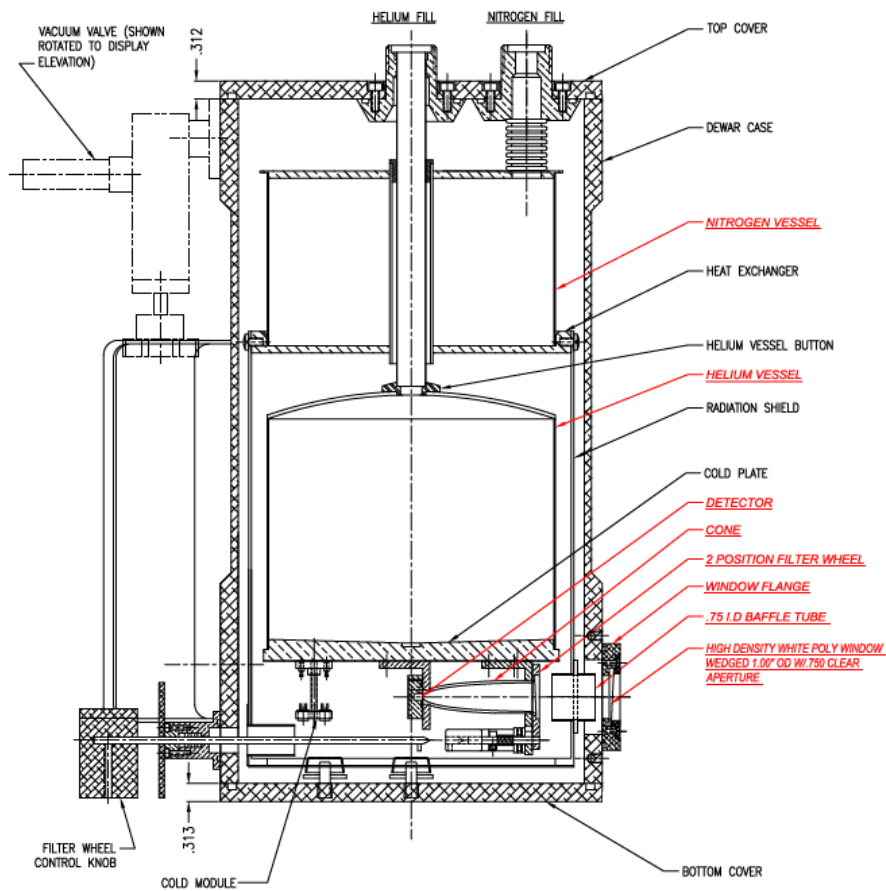
The probe light from the interferometer was allowed to travel through the wave guide, passed the sample located at the center of the superconducting magnet and reached the bolometer. The bolometer was used for detection of FIR wave through the sample. With the help of a computer connected directly to the spectroscopy (Opus-pro software used for controlling) a Fourier transform of the interferogram was automatically performed. After this conversion, the normalization of a reference spectrum measured with zero magnetic field ($T (B = 0 \text{ T})$) with the one taken at a magnetic field ($T (B \neq 0 \text{ T})$), then an absorption spectrum at each magnetic field was obtained.

The performance data for the present study was set as follows: Radiation source: high pressure mercury lamp, beam splitter: mylar for FIR, spectral resolution: 1 cm^{-1} , Detector: liquid helium cooled bolometer (filter 1), Spectral range: $0 - 800 \text{ cm}^{-1}$ ($0 - 24 \text{ THz}$), speed of moving mirror 10 KHz and scanning time was three hours for each sample. It is important to note that the combination of light source, detector, beam splitter and sample compartment window defines the IR measurement range.

3.3.3 Bolometer

Figure 3.13 shows typical schematic diagram for liquid cooled helium bolometer. A bolometer is simply a device for detection of incident radiation. It is also used to measure light in the far-infrared and millimeter-waves. A bolometer detects the incoming light wave through temperature variation of a thermometer like device attached to the absorber. All light wave that impinges on the detector will cause a temperature change resulting into change of resistance which is then measured as a voltage difference [52]. The detector element is an extremely sensitive thermistor that is cooled to liquid helium temperatures in order to decrease the thermal background.

As shown in Figure 3.13, since high efficiency is assured at low temperature, the bolometer system is housed with liquid helium dewar and a liquid nitrogen cooled radiation shield. The detector section consists of a light collecting cone assembly, vacuum-sealed wedged window and low noise



(a)



(b)

Figure 3.13 Schematic and outlook of bolometer for detection of terahertz wave.

electronics. The bolometer system is also equipped with a single cut-on filter which is operated manually to a two position filter wheels. The position of filter will depend on the measurement frequency range. In this work, the position filter one was selected for maximum detection.

3.3.4 CR experiments

Figure 3.14 shows schematic diagram for experimental set up for CR measurements. The terahertz transmission light was detected using a liquid helium cooled bolometer. through the original waveguide probe consisted from polished brass pipes. The transmission signals were converted by the bolometer from analog to digital and transmitted to the spectrometer for processing using direct connected computer which has Opus-pro software. The CR spectra were taken within the spectral

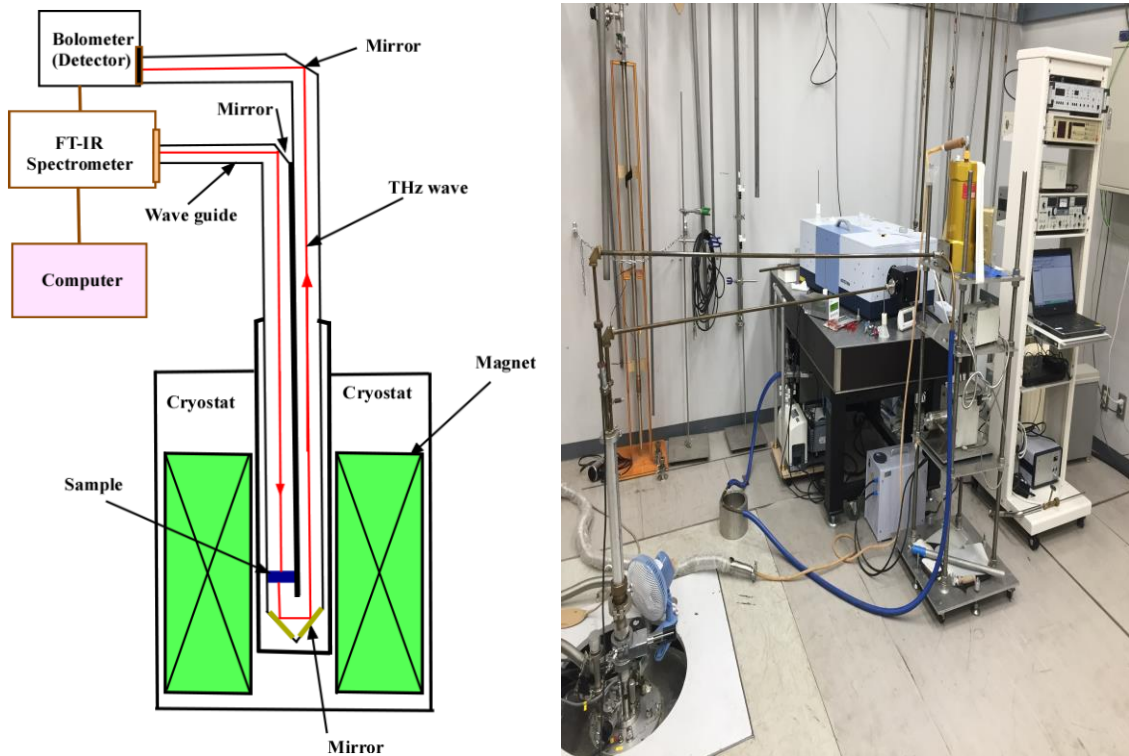


Figure 3.14 Schematic experimental set up for CR measurements. Four main components: 15T-superconducting magnet, spectroscope, bolometer and measuring probe are shown.

range of 0 and 800 cm^{-1} with a resolution of 1 cm^{-1} in the Faraday configuration. The experimental temperature was set to be $T = 1.7 \text{ K}$ for all the samples. Using this technique, accurate data were obtained from all the samples as shown and described in chapter four, five and six.

3.3.5 CR spectra

Figure 3.15 shows typical example of magneto-transmission of the CR for sample A. In order to obtain the CR spectrum for each magnetic field, the magneto-transmission, $T (B \neq 0)$, was systematically normalized to the reference transmission collected at zero magnetic field, $T (B = 0)$. In Figure 3.15 (a), the red line shows transmission taken at $B = 0 \text{ T}$ and blue line represents transmission at $B = 15 \text{ T}$. The normalized CR spectrum is shown in Figure 3.15 (b). Similar method was used for the all the samples.

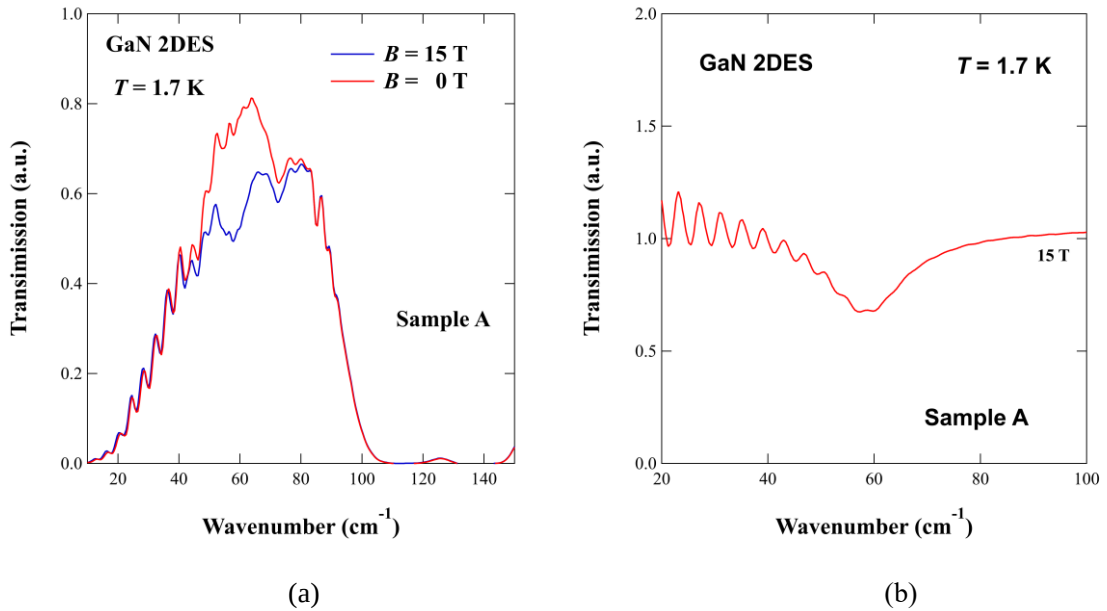


Figure 3.15 Typical example of magneto-transmission taken under a magnetic field $B = 15 \text{ T}$ at 1.7 K .

(a) Raw transmission spectra (b) Normalized CR spectra for sample

CHAPTER FOUR

Results and Discussion

AlGaN/GaN Heterostructures

4.1 Introductory statement

GaN has received considerable attention for its potential application in the power electronic and optoelectronic devices. Although band parameters such as the electron effective mass of GaN were determined, it is still unclear because the electron effective mass in 2D electron systems was reported widely between 0.18 and $0.27m_0$ [12, 13, 14, 53]. Figure 4.1 shows the carrier concentration dependence of some of the reported electron effective mass for AlGaN/GaN heterostructures [14].

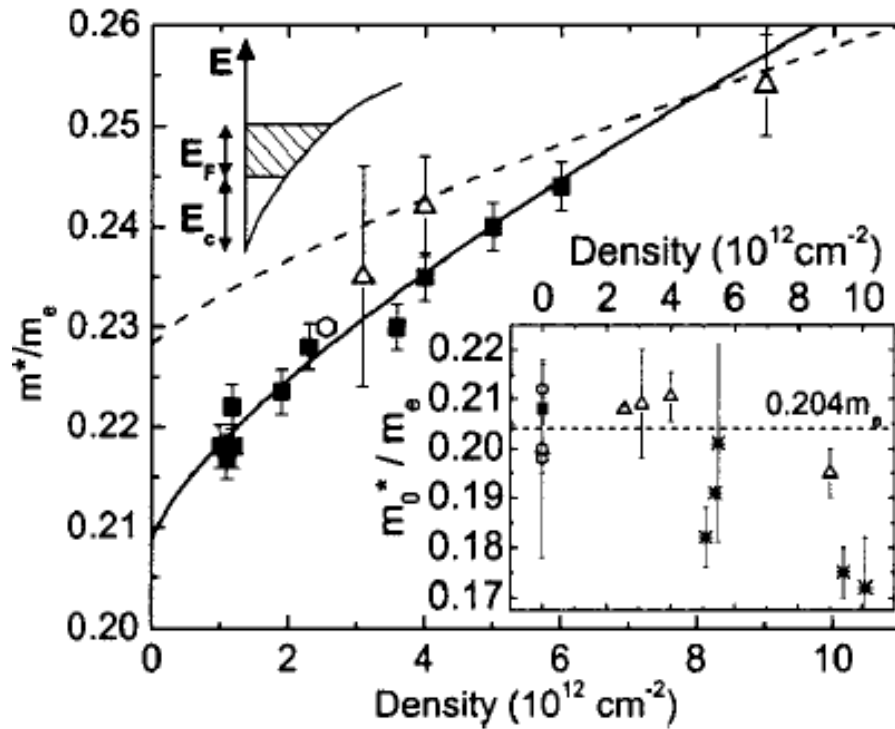


Figure 4.1 Carrier concentration dependence of the experimental values for electron effective mass in AlGaN/GaN heterostructures [14].

In this chapter, the results of cyclotron resonance measurements which was performed systematically in order to obtain the effective mass and clarify the reason for the discrepancy related to the widely reported mass are presented. In particular, the effective mass enhancement from the bulk value has been discussed from the view point of polaron effect because GaN has the larger electron-longitudinal-optical phonon interaction among III-V compounds.

Moreover, in high carrier concentration regime, the band non-parabolicity is another factor. Thus, carrier concentration dependence of the effective mass has been investigated in details for several samples with different carrier density. Magneto-transport measurements were carried out prior to cyclotron resonance measurements in order to investigate the sample quality, and for estimation of the effective mass, mobility and carrier concentration. In the following section, magneto-transport result is first displayed and discussed from the view point of their mobility.

4.2 Magneto-transport results

As described in chapter three, magneto-transport experiments were carried for checking the sample quality and realization of 2DES. The typical magneto-transport data for GaN heterostructure samples B and C are shown in Figure 4.2 (a) and (b), and the result for sample A can be found in our paper, D. Kindole *et al.*, [53]. The Shubnikov-de Haas (SdH) oscillation was observed clearly at integer filling factors in the magneto-resistance data for all samples. In addition, the quantum Hall plateaus were observed in the Hall resistance data, in particular, on the high magnetic field side indicating to realize high electron mobility in these samples. Consequently, it is possible to study cyclotron resonance (CR) because the CR condition, $\omega_c\tau = 1$ (τ is the scattering time) can be satisfied.

The Landau plot of the SdH oscillation minima against the inverse magnetic field (see Figure 4.3) was used to determine the carrier concentration $n_s = 8.5 \times 10^{12} \text{ cm}^{-2}$ for GaN sample B (30 nm). Therefore, using this data, the kinetic energy of the electrons above the band-edge (E_k) and the Fermi

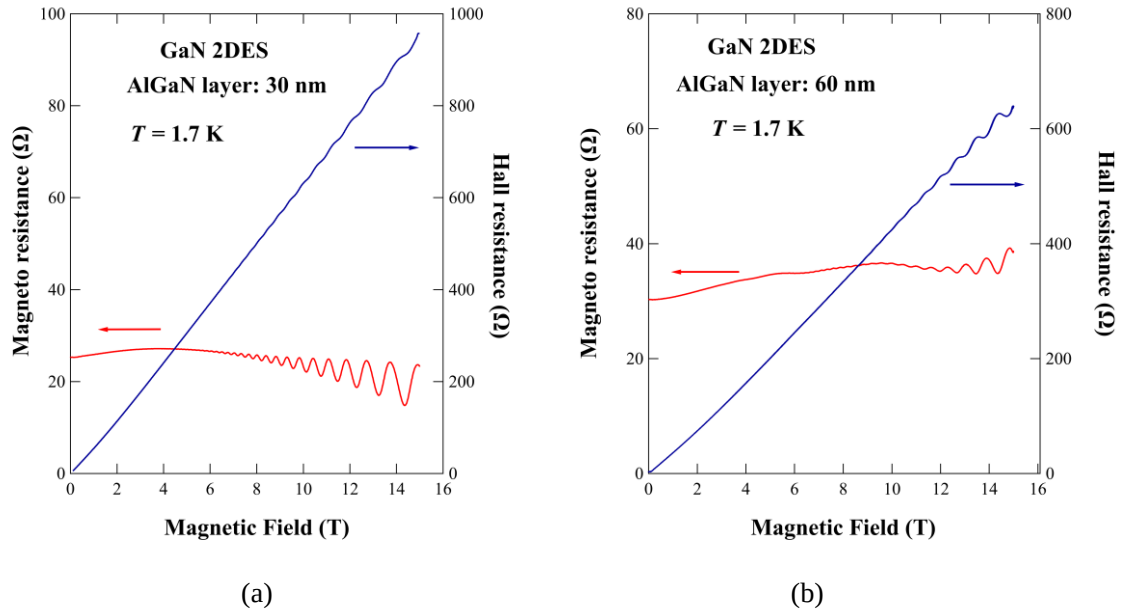


Figure 4.2 Typical magneto-transport results for GaN 2DES at $T = 1.7$ K for sample B (30 nm) and C (60 nm). The Shubnikov-de Haas oscillation and quantum Hall features were clearly observed at integer filling factors indicating to realize high electron mobility in all samples.

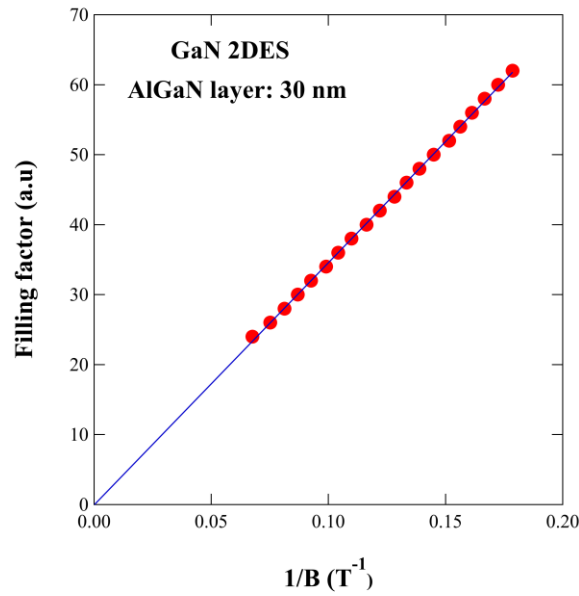


Figure 4.3 The Landau plot of the SdH minima against the inverse magnetic field for sample B.

Table 4.1 Sample details, the carrier concentration and mobility (at 1.7 K).

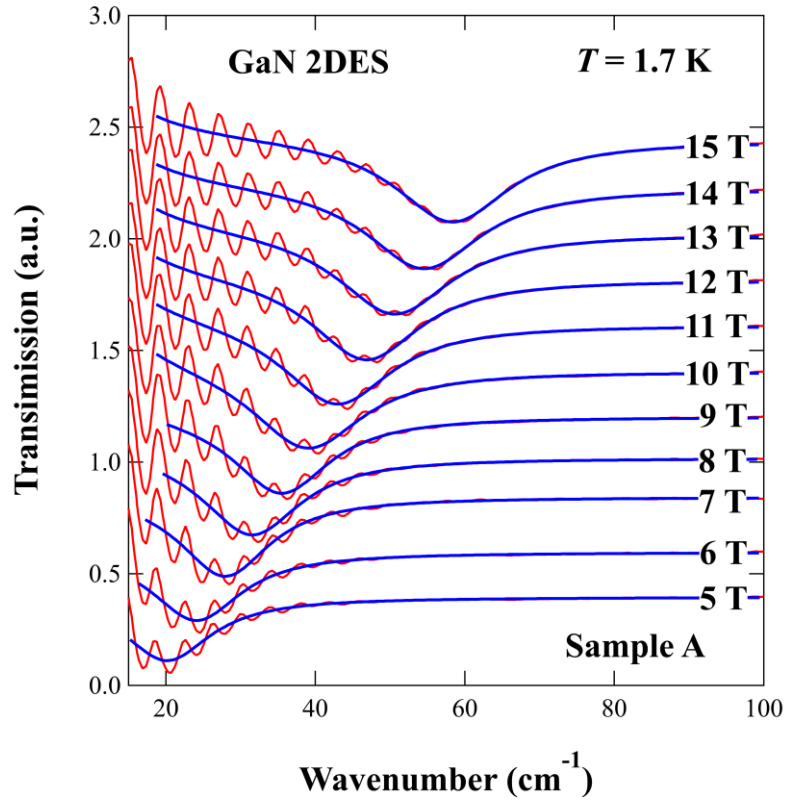
Sample	Barrier thickness (nm)	n_s (cm ⁻²)	E_F (meV)	E_k (meV)
Al _{0.25} Ga _{0.75} N/GaN	15	5.4 x 10 ¹²	64.7	53.5
	30	8.5 x 10 ¹²	101.9	72.5
	60	1.1 x 10 ¹³	119.9	80.7

energies (E_F) of the 2D electron systems due to electron confinement and band filling was estimated using equation (2.70) and (2.71) respectively. Similar characteristics for magneto-resistance was estimated from samples A and C. Table 4.1 summarizes the results from the analysis of the magneto-transport measurements of AlGaIn/GaN two-dimensional electron system taken at $T = 1.7$ K.

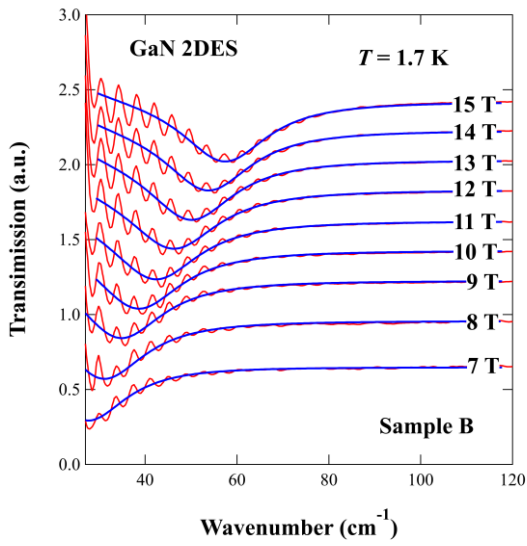
4.3 CR results and discussion

As discussed in chapter three, the CR measurements were carried out at high magnetic field up to $B = 15$ T at $T = 1.7$ K. In this section the CR results of GaN 2DES are discussed in details. Figure 4.4 shows magnetic field dependence of the CR spectra for sample A, B and C taken at $T = 1.7$ K. The resonant absorption was clearly observed for each magnetic field, and the resonance shifts to the higher energy with increasing magnetic field. The interference effect in the CR transmission between the surface and the back surface of the sample was eliminated successfully on the high wavenumber side by preparing a wedged sample. Each curve was successfully fitted using theoretical magneto-transmission curve of the 2DES as shown with blue solid curves in Figure 4.4 [39].

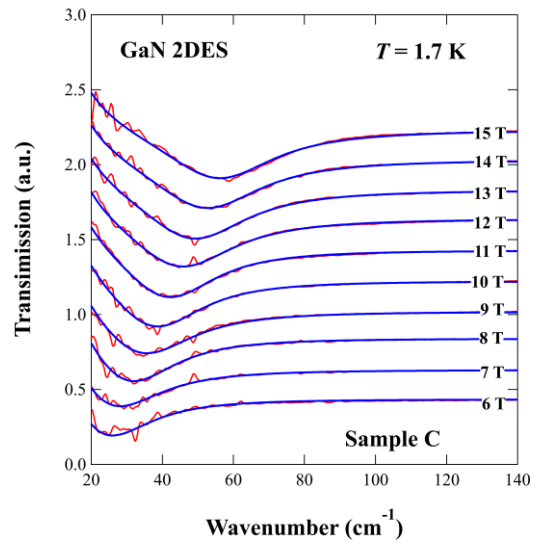
Therefore, accurate effective mass and scattering time were obtained directly from the curve fitting procedure. In addition, the CR energy and mobility were determined using the following relation,



(a)



(b)



(c)

Figure 4.4 Typical magnetic field dependence of the CR spectra for (a) Sample A, (b) Sample B and (c) Sample C. The blue curves on the CR spectra indicates the fitting results.

$E_c = \hbar\omega_c$ and $\mu = \frac{e\tau}{m^*}$ respectively. Figure 4.5 shows magnetic field dependence of the (a) effective mass and (b) CR energy for sample A, B and C. Two things were observed in Figure 4.5(a). First, the effective mass of the 2DES becomes heavier with increasing magnetic field. It was originally suggested that, this is probably due to the contribution from the resonant polaron effect because GaN has a large electron- longitudinal (LO)-phonon interaction among III-V compounds [12, 43]. Secondly, the effective mass tends to increase with increasing carrier concentration. It was also urged that, in high carrier density, the band non-parabolicity is another factor for the effective mass enhancement in semiconductors [54]. In this research work, in order to investigate the origin of the effective mass enhancement observed in Figure 4.5 as well as the widely effective mass values reported by numerous groups, major factors for the mass enhancement are detailed investigated.

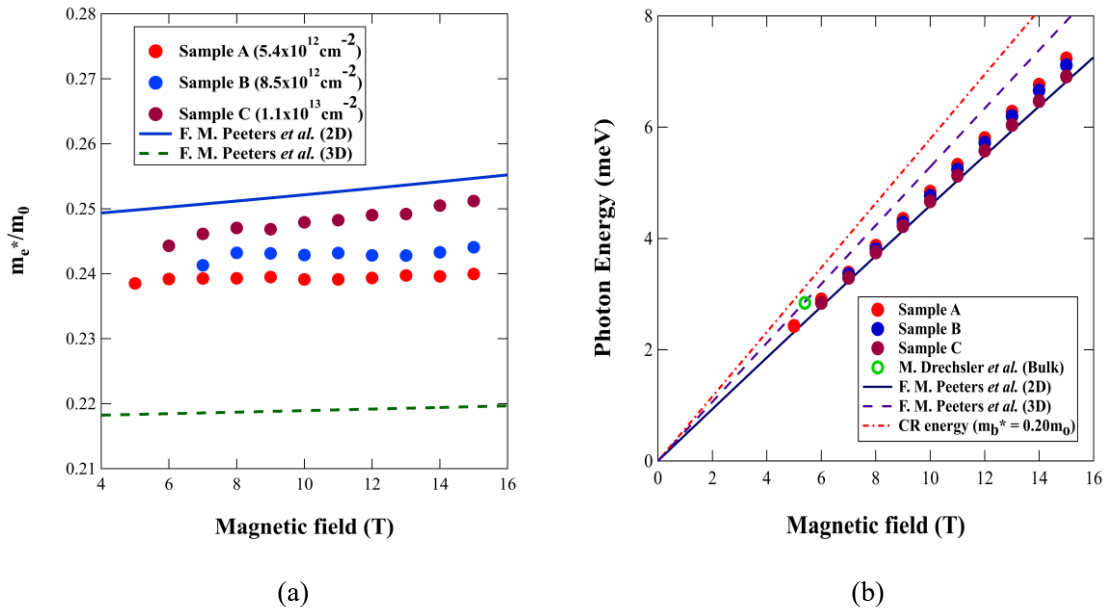


Figure 4.5 Magnetic field dependence of the (a) effective mass and (b) for sample A, B and C. Theoretical lines are compared with present CR data (solid circles).

4.3.1 Band non-parabolic effect

In chapter two, band non-parabolicity was discussed in details. For parabolic band energy the effective mass is constant. However, in 2D electron systems (2DES) as the carrier concentration is raised, the CR mass is increased. This is because the increasing of carrier concentration will shift the Fermi energy (E_F) as well as kinetic energy (E_k) of the confined 2DES. Consequently, in 2D systems, large increase of carrier densities and confinement effect results into band non-parabolicity. The band non-parabolic effect in the triangular potential at the AlGaIn/GaN heterointerface can be evaluated with using the two-band model. In two-band model, an increase of the effective mass due to band non-parabolicity is given in equation (2.69), where K represents a non-parabolic parameter, the confirmed energy is given by $E = E_F + E_k$, and for GaN, $E_g = 3.5$ eV, $m_o = 0.2m_e$ [12, 14, 54].

Figure 4.6 shows carrier concentration dependence of the effective mass obtained through CR measurements. The open square is the CR effective mass from Ref. [14], and the open circle shows the results which was also obtained through CR experiments [54]. Taking into account of band non-parabolicity, Syed *et al* [14] estimated the band edge mass of wurtzite GaN as $0.208m_o$, using multiband model. This is because two band model could not explain their data. In addition, in order to explain their data, the parameter K was used as $K = 2.5$, with the view that large value of K accounts for the effect of higher conduction band (see dashed line in Figure 4.6). This estimation could explain their experimental data, in particular, for low carrier concentration region. However, their assumption, could not explain perfectly all data especially, for higher carrier concentration regime (see Ref. [54] as well as the present data shown with solid circle). Such a model was used to understand the band non-parabolic effect in low carrier concentration regime in the case of GaAs quantum well system in the 1988, because carrier density up to only $n_s \approx 10^7$ cm⁻² could be realized [55]. In the early study of the band non-parabolic effect to the effective mass of n-type GaN 2DES, the contribution of non-parabolicity to the mass enhancement was estimated using two band model (parameter $K = 1$). This

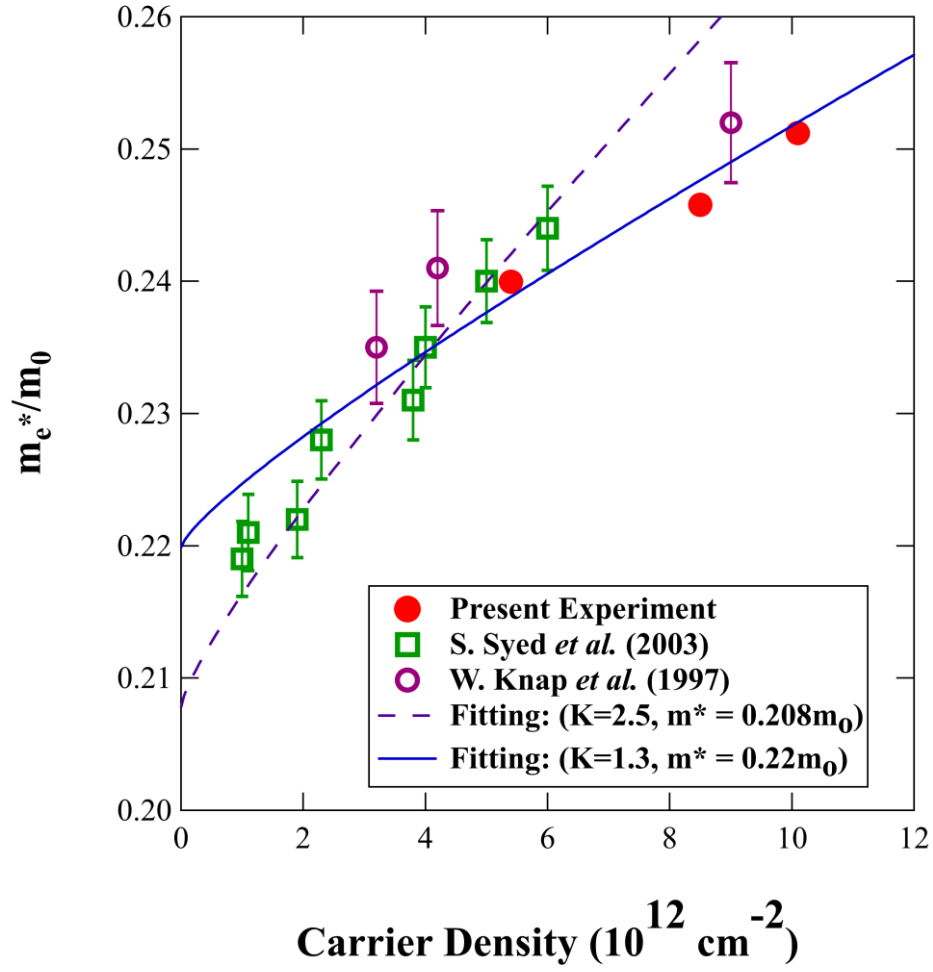


Figure 4.6 Carrier concentration dependence of the effective mass in GaN heterostructures measured by different groups. The solid circles represent the present CR data at 15T and contain very small error.

approximation was carried out because a higher carrier concentration beyond $n_s \sim 10^{12} \text{ cm}^{-2}$ could be realized in the GaN 2DES [54, 56]. The band-nonparabolicity effect to the effective mass can be negligible basically in the case of wide band-gap semiconductors such as GaN ($E_g = 3.5 \text{ eV}$) at low carrier density. However, as discussed previously, under high carrier concentration, the band-nonparabolicity is possible to make a large contribution for the mass enhancement. The non-parabolic contribution to the effective mass of GaN was estimated as 10% in the case of a high carrier

concentration around $n_s \sim 10^{13} \text{ cm}^{-2}$ [54]. In addition, for GaN with carrier densities below $n_s \sim 10^{12} \text{ cm}^{-2}$ the effective mass increase was estimated as 15%, in which only 5% was assigned to band non-parabolicity and 10% was explained by electron-LO phonon interaction because GaN has large coupling constant among III-V compounds [54, 55].

The carrier concentrations of the present data were obtained as $n_{sA} = 5.4 \times 10^{12} \text{ cm}^{-2}$ and $n_{sB} = 8.5 \times 10^{12} \text{ cm}^{-2}$ for sample A and B which are lower than $n_s \sim 10^{13} \text{ cm}^{-2}$, so that the band non-parabolic contribution could be estimated small. In case of sample C which has high carrier concentration ($n_{sC} = 1.1 \times 10^{13} \text{ cm}^{-2}$), the band non-parabolic is expected to be higher. However, in Figure 4.6, the band non-parabolic parameter $K = 2.5$ (dashed line) failed to explain the data from the large carrier density samples as discussed above. Therefore, appropriate band non-parabolic parameter K should be chosen to explain the high carrier concentration results.

Theoretically, the parameter K varies depending on materials, and in the ideal two-band model regardless of the materials, the parameter $K = 1$. This parameter was successfully used to understand the band non-parabolic contribution to the effective mass in GaN 2DES for wide carrier concentration $n_s \approx 3.1 \sim 9.0 \times 10^{12} \text{ cm}^{-2}$ [54, 56]. In the case of GaAs heterostructures ($n_s \approx 1.4 \times 10^{11} \text{ cm}^{-2}$), the parameter $K = 1.4$ was obtained by using five-band model [40]. Moreover, the band non-parabolic effect in low carrier concentration regime for GaAs quantum well was estimated using modified two-band model as $K = 1.35$ in the early 1988, because low carrier density up to only $n_s \approx 10^7 \text{ cm}^{-2}$ could be realized [55].

In Figure 4.5 (a), the solid circle represents the present CR mass. As it is clearly seen, the fitting (dashed line) with $K = 2.5$ could not explain the present data, in particular, high carrier concentration. Hence, it is suggested that the appropriate value of parameter K to be less than two ($K < 2$), which is also supported by references [40, 54]. Using the famous two-band model $m_n = m_o^*(2KE/E_g)$, where $E_g = 3.5 \text{ eV}$, $m_b = 0.2m_o$ [12, 14, 54], $E = E_F + E_k$, with only one variable parameter K , a new fitting

(solid line) procedure was successfully achieved, and a new band non-parabolic parameter is obtained as $K = 1.3$. The new fitting line ($K = 1.3$) explain clearly all the data in comparison to the dashed line ($K = 2.5$) in Figure 4.6. From this fitting the band edge mass is obtained as $0.22m_0$. Therefore, overall it was felt that the best fit to the data is when $K = 1.3$, which in this work is recommended as a parameter for explaining band non-parabolic contribution in GaN 2D electron system.

However, the obtained band edge mass $0.22m_0$ is still large from the reported value of $0.20m_0$ [12] which was also recommended in the review [20] and entered in most textbooks [57, 58] as a common-used parameter for the effective mass of electron in GaN material. Therefore, another contribution is needed to explain the large enhancement of the effective mass from the band bare mass, $\Delta m_c \sim 26\%$, in the present work.

4.3.2 Polaron effect

As discussed in chapter two, in polar semiconductors such as group III–V compounds, it is the polaron mass that is actually obtained in the CR measurements [12]. The CR mass exceeds the bare electron mass by a factor of about $1+\alpha/6$, depending on the strength of the electron–LO phonon interaction. In the magnetic field dependence of the CR energy, as $\hbar\omega_c$ approaches $\hbar\omega_L$, the effective mass becomes heavier and heavier, until the energy curve is flattened close $\hbar\omega_c = \hbar\omega_L$ [43, 59, 60].

Figure 4.5 (b) shows magnetic field dependence of the CR energy for GaN. The solid circle denotes the present data. A non-linear dependence of the CR energy against the magnetic field is observed, indicating that the electron effective mass becomes heavier with increasing magnetic field. The open circle is the CR experimental result for a bulk n-type GaN, which was obtained by Drechsler *et al.* with using a far-infrared laser [12]. Drechsler estimated the bare band mass as $m_b^* = 0.20m_0$ from the analysis of polaron effect because GaN is a polar semiconductor with a large electron-LO phonon interaction among III-V compounds. The electron-LO phonon coupling constant (α) was used as α

=0.49 in their analysis. The dashed and dotted lines in Figure 4.5 (b) show the CR energy calculated by using the bare band mass, $m_b^* = 0.20m_0$. The theoretical line with m_b^* cannot explain the present CR results because the effective mass becomes heavier than the bare band mass; hence, an additional contribution to the effective mass should also be assumed to the present results.

In Figure 4.5 (b), the solid curve and the dashed curve represent the theoretical polaron CR energy in the two-dimensional (2D) and the three-dimensional (3D) system based on similar equations (2.76) and (2.77) as discussed in chapter two [43], where ω_L is the longitudinal optical phonon energy ($\omega_L = 92$ meV) and N corresponds to the Landau index. The coupling constant (α) and the bare band mass (m_b^*) were used as $\alpha = 0.49$ and $m_b^* = 0.20m_0$, respectively. These formulas can be applied only in the low-energy region far below the LO-phonon energy (weak magnetic field limit). The 3D polaron energy calculation (dashed curve in Figure 4.5(b)) is in good coincidence with the CR data for the bulk n-type GaN obtained by Drechsler *et al.* (open circle in Figure 4.5(b)). This means that the polaron contribution should be important for understanding the electron effective mass in GaN. On the other hand, the magnetic field dependence of the present CR data (solid circles in Figure 4.5(b)) cannot be explained by the 3D polaron energy calculation because the data is located far away from the 3D line. However, since the present data are close to the 2D polaron energy, therefore can be explained from this approach. The effective electron-phonon coupling in the 2DES is expected to be larger than in the 3D system because of the carrier confinement at the heterointerface [53].

In Figure 4.5(a), the solid line and the dashed line represent the 2D and the 3D calculation results for the polaron mass as a function of the magnetic field based on equations (2.76) and (2.77). The effective mass obtained from the present CR results increases slightly with increasing magnetic field. The present results show clearly that the obtained effective mass (solid circles in Figure 4.5(a)) is heavier than the 3D calculation (dashed line) but smaller than the ideal 2D one (solid line). This reduction of the CR mass obtained from the ideal 2D calculation is probably due to the reduction of

the polaron effect because of the finite width of the confinement potential in the quasi-2D system.

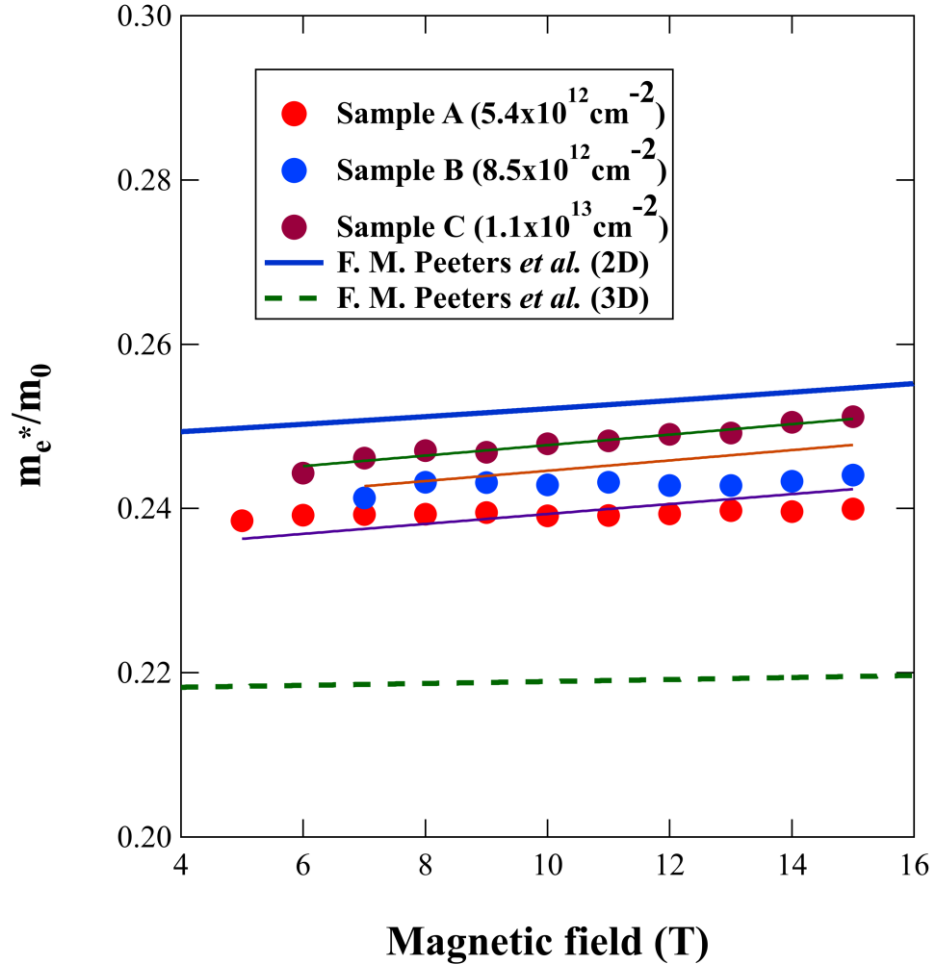


Figure 4.7 Magnetic field dependence of the effective mass for sample A, B and C. Fitting procedure was successful performed on the present CR data (solid circles), and effective coupling constant was obtained as free parameter.

A detailed theoretical study of the effective mass has already been performed in the GaN 2DES taking into account both the polaron effect and the band non-parabolicity up to ultra-high magnetic fields [59]. In 2D systems, the polaron coupling is also suppressed because of the screening effect and

the occupation effect for higher carrier concentration beyond $n_s \geq 10^{12} \text{ cm}^{-2}$. In addition, for GaN with carrier densities around $n_s \sim 10^{12} \text{ cm}^{-2}$ the effective mass increase was estimated as 15%, and 10% of this was explained by polaron effect because GaN has a large coupling constant among III–V compounds [56]. Therefore, magnetic field dependence of the effective mass in Figure 4.7 could be also explained from the reduction of the polaron effect in the high density quasi-2D electron system. Despite of screening effect in 2DES, for materials with huge coupling constant like GaN, the polaron contribution still remain.

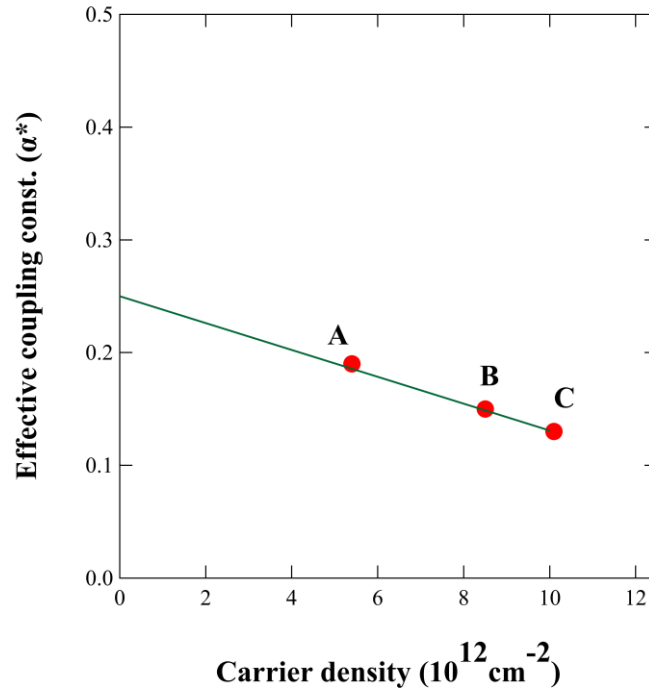


Figure 4.8. Carrier density dependence of the effective LO-coupling for present CR data obtained through the fitting procedures according to equation (4.1).

To conclude on this, it is hard to assign the large effective mass enhancement of the present data to neither band non-parabolic nor polaron effect only. This is under assumption that, if we believe the

value of K then effective coupling for explaining the present data can be obtained in order to have better description of all experimental data. Therefore, a combined effect analysis was performed in order to separate the polaron effect and band non-parabolicity contribution to the effective mass. From Figure 4.7, using reasonable value of $K = 1.3$ obtained from the non-parabolic curve (see solid fitting line in Figure 4.6), the effective coupling constant α^* for each sample was obtained through fitting procedures. The combined fitting equation used to obtain the effective coupling constant is given as:

$$m = (NP) \times (Pl) m_o \quad (4.1)$$

Where NP is the effective mass with only band non-parabolic contribution according to equation (2.69) and Pl is assigned to polaron mass (see equation (2.76)).

Table 4.2. The effective coupling (α^*) for the present CR data.

Sample	n_s (cm ⁻²)	α^*
A	5.4×10^{12}	0.19
B	8.5×10^{12}	0.15
C	1.1×10^{12}	0.13

Figure 4.8 shows carrier density dependence of the effective coupling for present CR data obtained through the fitting procedures according to equation (4.1) with only one variable α^* . The effective coupling constants were found to decrease as the carrier concentration is increased. This is due to the fact that the polaron effect becomes low with increasing carrier density because of the screening effect. On the other hand, the band non-parabolic becomes evident as the carrier density becomes large [54]. The obtained effective coupling constant (α^*) are summarized in Table 4.2. This tendency is quite appropriate because of the screening effect, and this effective LO-phonon coupling can qualitatively explain well the present work and other people's results. Therefore, it is concluded

that the two-dimensional electron mass in GaN heterostructures is strongly affected by the polaron effect and the band non-parabolicity. From this result, it is finally solved the contradiction in relation to the reported value of the effective mass in AlGaIn/GaN heterostructures in the present work.

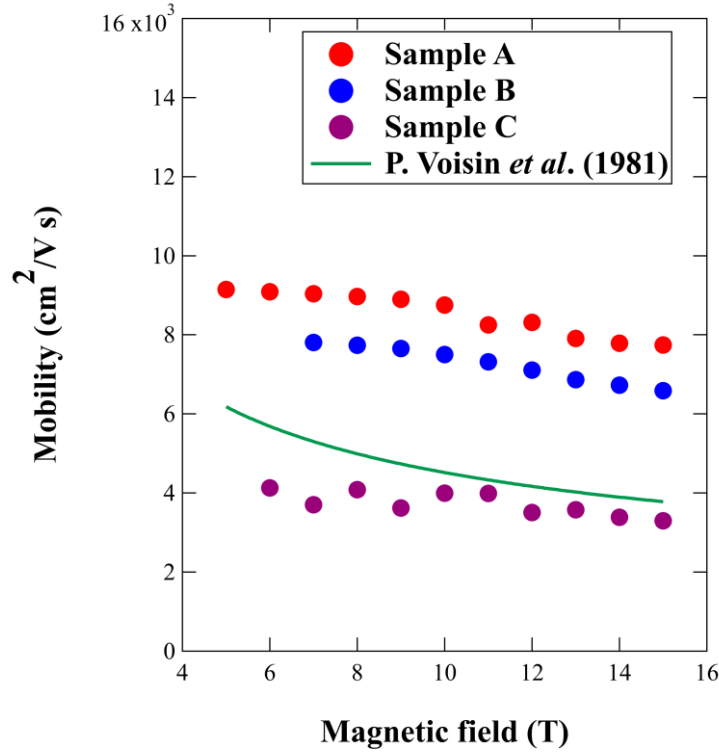


Figure 4.9 Magnetic field dependence of the electron mobility for the three sample.

4.3.3 Electron mobility

Figure 4.9 shows magnetic field dependence of the electron mobility in GaN heterostructures. As discussed in section 4.2, the scattering time τ , was extracted from the resonant line-width for each CR spectrum in sample A, B and C. The electron mobility μ was calculated from these data using the relation, $\mu = \frac{e\tau}{m^*}$ (see Figure 4.9). The electron mobility of the 2DES decreases gradually with increasing magnetic field. This is partially due to the enhancement of the 2D electron effective mass against the magnetic field shown in Figure 4.5 (a), and mainly due to the decrease of the carrier

scattering time in the magnetic field. Similar variation of the scattering time against the magnetic field was also observed in the CR line-width in GaAs heterostructures (see the solid line in Figure 4.9). The CR width broadening under the magnetic field can be explained reasonably if the CR width reflects directly on the broadening of the Landau level width in relation to the short-range carrier scattering by impurities, defects, and the interface roughness [61]. Therefore, the short-range scattering could play a main role in determining the CR line-width in the present samples and the magnetic field dependence of the mobility in Figure 4.9.

4.4 Conclusions

In summary, the CR experiments in AlGa_N/Ga_N heterostructures have been studied at high magnetic fields. The CR absorption was clearly observed at each magnetic field. The obtained electron effective mass was found to increase with increasing both magnetic field and carrier density. The effective mass of Ga_N 2D electron systems is enhanced almost 26% from the bare electron mass of the bulk Ga_N.

The huge effective mass enhancement has been discussed from the viewpoint of the band non-parabolicity due to high carrier density and polaron effect because Ga_N have a large electron-LO phonon interaction among III-V compounds. It is found that the two-dimensional electron mass in Ga_N heterostructures is strongly affected by the band non-parabolicity and electron-phonon interaction. This result has finally solved the contradiction in relation to the reported value of the effective mass in AlGa_N/Ga_N heterostructures.

In addition, the magnetic field dependence of the electron mobility in the Ga_N 2DES is found to decrease gradually with increasing magnetic field. This is mainly due to the variation of electron scattering time through the broadening of the Landau levels because of the short-range scattering. The present result is explained perfectly through the theoretical calculation.

CHAPTER FIVE

Results and Discussion

AlGa_xN/InGa_{1-x}N Heterostructures

5.1 Introductory statement

InGa_xN has attracted significant attention for photovoltaic application. This is because the bandgap energy can be varied continuously between 0.7 eV (InN) and 3.5 eV (Ga_xN), providing a full-solar-spectrum system for multijunction solar cells [8, 16]. However, detailed electronic properties related to InGa_xN two-dimensional electron systems have not been reported yet because it is difficult to obtain a high-quality InGa_xN film [62, 63].

In this chapter, cyclotron resonance experimental results in AlGa_xN/In_xGa_{1-x}N heterostructures ($x = 0 \sim 7\%$) are discussed in details. In particular, resonant absorption and Shubnikov-de Hass (SdH) oscillation are the first observation in InGa_xN 2D electron system. The effective mass obtained from the CR result is in good agreement with the one from the temperature dependence of the SdH oscillation. Moreover, indium concentration dependence of the effective mass and various scattering mechanisms have also been investigated in details.

First magneto-transport results for checking the sample quality as well as the presence of two-dimensional electron gas are displayed followed by the discussion of CR and temperature dependence of the SdH oscillation.

5.2 Magneto-transport results

The typical magneto-transport data for In_xGa_{1-x}N 2DES up to $B = 15$ T for sample with indium concentration; $x = 4.1\%$ and 6.8% are shown in Figure 5.1. The result for sample with $x = 5.0\%$ indium content can be found in our paper [62]. The SdH oscillation was observed clearly at integer filling factors in the magneto-resistance data. In addition, the quantum Hall like features were also

observed in the Hall resistance data. These achievements are useful not for understanding the physics behind this material but also for InGaN film growth and for development of new devices using InGaN crystals.

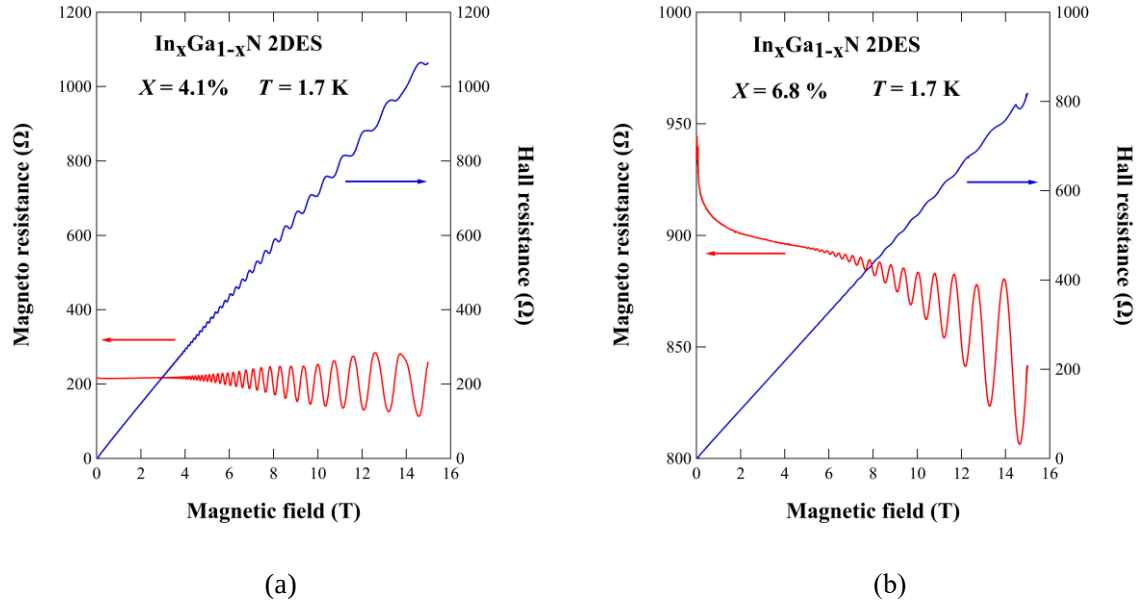


Figure 5.1 Typical magneto-transport data for AlGaIn/ $\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructures. The SdH oscillation and quantum Hall plateau are clearly observed from the magneto-resistance and Hall resistance data. This indicates that high mobility 2D electron system is realized. The indium content is indicated in each panel.

In Figure 5.2, after subtracting the background and performing a Fast Fourier Transform (FFT) on the SdH oscillation as function of inverse magnetic field ($1/B$), one dominant oscillation frequency due to single occupied electron subband was obtained. Every oscillation frequency corresponds to a (partially) filled subband, therefore, from the FFT peak position, the carrier concentration of sample with $x = 4.1\%$ indium content was determined using the relation, $n_s = 2eF/h$ (where F is oscillation

frequency) as $n_s = 7.0 \times 10^{12} \text{ cm}^{-2}$. This result was found to be in good agreement with the carrier concentration obtained from the Landau plot of the SdH oscillation minima against the inverse magnetic field presented in chapter four. The carrier concentration of sample $x = 5.0 \%$ and $x = 6.8 \%$ was obtained as $7.1 \times 10^{12} \text{ cm}^{-2}$ and $7.8 \times 10^{12} \text{ cm}^{-2}$ respectively.

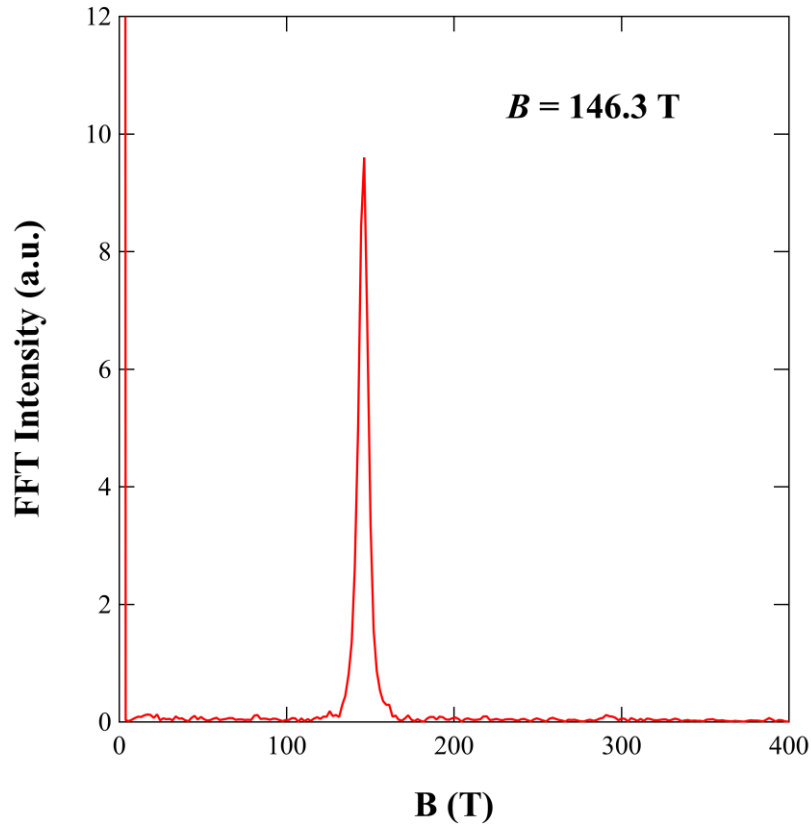
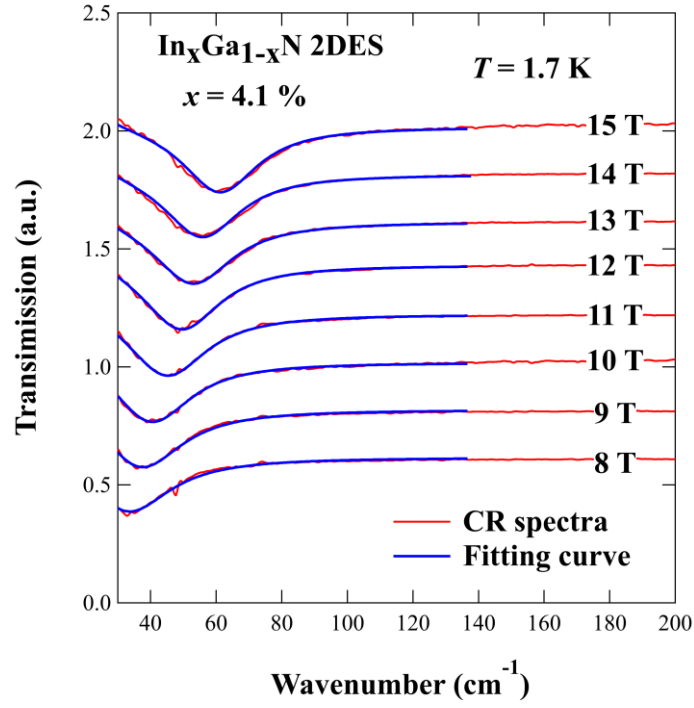


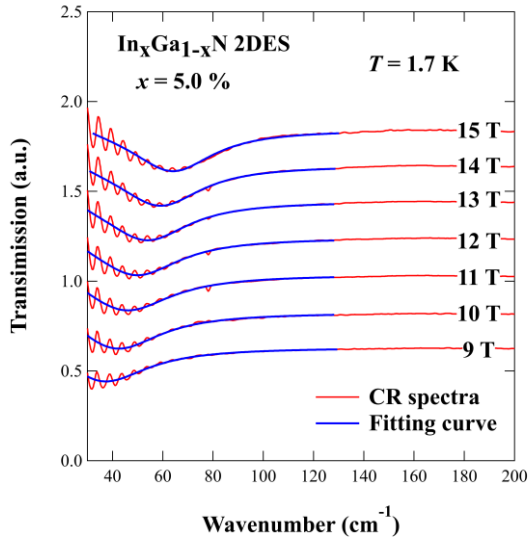
Figure 5.2 FFT data calculated from magneto-resistance data (R_{xx}) for sample with $x = 4.1 \%$ indium content. The carrier concentration was determined as $n_s = 7.0 \times 10^{12} \text{ cm}^{-2}$.

5.3 CR results and discussion

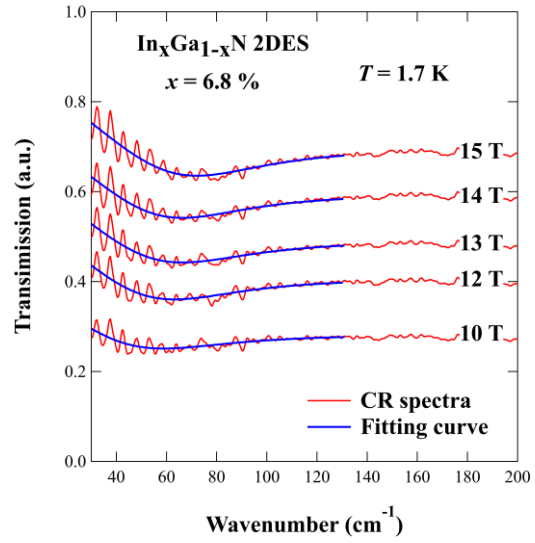
The CR absorption spectra for $\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructures taken at magnetic fields ranging from $B = 8 \sim 15 \text{ T}$ are shown in Figure 5.3 (Red color). The resonant absorption, which shifts to higher energies with increasing magnetic fields were clearly observed even in case of higher indium content



(a)



(b)



(c)

Figure 5.3 Magnetic field dependence of the CR spectra for $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2DES measured between $B = 8$ T and 15 T at $T = 1.7$ K. (a) $x = 4.1$ %, (b) $x = 5.0$ %, (c) $x = 6.8$ %. The blue curves on the CR spectra indicate the fitting results using theoretical magneto-transmission fitting curve of the 2DES [39].

sample ($x = 6.8\%$). This suggests that we can realize high mobility two-dimensional electron gas in these samples, and a clear evidence was seen in the absorption resonance of sample $x = 4.1\%$ and $x = 5.0\%$ which demonstrated a narrower line-width than high indium content sample. In case of sample $x = 6.8\%$, a broader line-width of the absorption resonance because of its low electron mobility in comparison with other samples. The mobility of the 2D electron gas decreases with increasing indium composition due to alloying effect [64].

Table 5.1 CR experimental results obtained at 1.7 K.

AlGa _N /In _x Ga _{1-x} N	$x = 0\%$	$x = 4.1\%$	$x = 5.0\%$	$x = 6.8\%$
Effective mass (m/m_0)	0.242	0.229	0.226	0.222
Scattering time (s)	1.1×10^{-12}	5.29×10^{-13}	3.32×10^{-13}	1.34×10^{-13}
Mobility ($\text{cm}^2/\text{V}\cdot\text{s}$)	7,810	4,350	2,880	1,100

Successful fitting procedures were performed for all the resonant absorptions using theoretical magneto-transmission fitting curve of the 2DES [31]. In Figure 5.3, the blue solid curve shows the fitting line. The interference effect in the CR spectra between the surface and the back surface of the sample was also eliminated successfully (above 30 cm^{-1}) by preparing a wedged sample. The electron effective mass (m^*) and scattering time (τ) were directly obtained from the fitting procedures. The obtained parameters for the present In_xGa_{1-x}N heterostructure samples from both the CR and magneto-transport measurements are summarized in Table 5.1.

From Table 5.1, the cyclotron electron mobility as high as $\mu = 4,350 \text{ cm}^2/\text{Vs}$ at 1.7 K was obtained from sample, $x = 4.1\%$ indium content, which is very high compared to the recently reported value. So far, the highest reported mobility of bulk In_xGa_{1-x}N was less than $40 \text{ cm}^2/\text{V}\cdot\text{s}$ [63], and this mobility is far from being suitable for magneto-transport and CR study even at high magnetic fields

and very low temperature condition. Furthermore, the electron mobility obtained from the present samples were found to drastically decrease with increasing indium concentration, indicating strong influence of indium to the sample quality. This could be attributed to alloy scattering and interface scattering in $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2DES especially at high indium concentration [64].

Figure 5.4 shows indium composition dependence of the measured effective mass for $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2DES ($x = 0 \sim 7\%$). The effective mass with $x = 0\%$ is obtained from GaN heterostructure (sample B) which is discussed in chapter four. In Figure 5.4 (a), the obtained effective mass for $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2DES ($x = 0 \sim 7\%$) was found to vary gradually with changing indium composition (x). This indicates that the indium concentration was successfully induced into the sample and has significant influence to the effective mass because InN [15] has lighter effective mass than GaN. In order to understand indium concentration dependence of the effective mass for the entire indium concentration, linear fitting to the mass was tried. The fitting line was found to cross x-axis before reaching 100% indium concentration indicating negative mass. Thus, linear extrapolation cannot explain the present data.

Recently, the effective mass of InN 2D electron system was obtained using temperature dependence of the SdH oscillation as $m_{\text{InN}}^* = 0.10m_0$ [15]. In Figure 5.4 (b), effective mass of InN was added to the panel, and tried to linearly fit together with the present results. Accurate linear fitting between GaN and InN was obtained, and showed that it could explain well the present data. However, when expanded around the present results, the linear fitting line was found to be far away from the present results. This further indicates that both linear extrapolation and interpolation for the entire indium composition cannot explain the present results through the linear dependence.

Figure 5.5 shows indium composition dependence of various effective masses obtained from both $\text{In}_x\text{Ga}_{1-x}\text{N}$ 3D and $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2D system ($x = 0 \sim 1$). The solid circles represent the present experiments for $\text{In}_x\text{Ga}_{1-x}\text{N}$ samples. Similar CR analysis in $\text{In}_x\text{Ga}_{1-x}\text{N}$ with $x = 0$ was also carried out previously by many groups, and electron effective mass ranging from $m_{\text{GaN}}^* = 0.2 \sim 0.27 m_0$ taking into account the

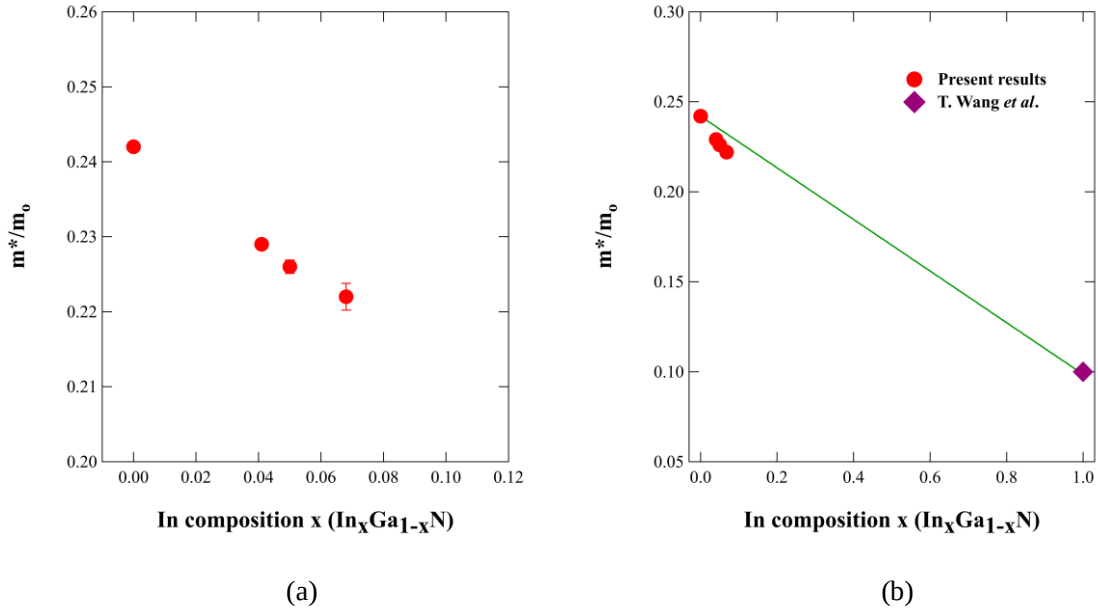


Figure 5.4 shows indium composition dependence of the measured effective mass for $\text{In}_x\text{Ga}_{1-x}\text{N}$ 2DES ($x = 0 \sim 7\%$). (a) Results of the present experiments (b) Fitting results of the present data and the results from reference [15].

influence of both polaron and band-nonparabolicity was reported [12, 13], and shows good agreement with the present results (sample B). The solid diamond indicates the effective mass that was recently obtained by Wang *et al* [15].

In Figure 5.5, the solid curve between the mass of InGaN 2DES (solid circle) and InN 2DES (solid diamond) represent the fitting result obtained using similar Vegard's law reported by Vurgaftman *et al* [20]. This is because the band structure of material is not only governed by the band gap energy but also the electron mass, similar Vegard's law can be used to understand the indium concentration dependence of the effective mass for the entire indium content as shown in equation (2.2) in chapter two. The bowing parameter b_m describes the deviation of the effective mass from the linear composition dependence between the GaN ($x = 0$) and InN ($x = 1$) end materials. From the curve

fitting procedures, the bowing parameter is obtained as $b_m = 0.174 m_0$. The bowing curve explains well the present experiments displaying non-linear relationship for the entire indium concentration range $x = 0 \sim 1$.

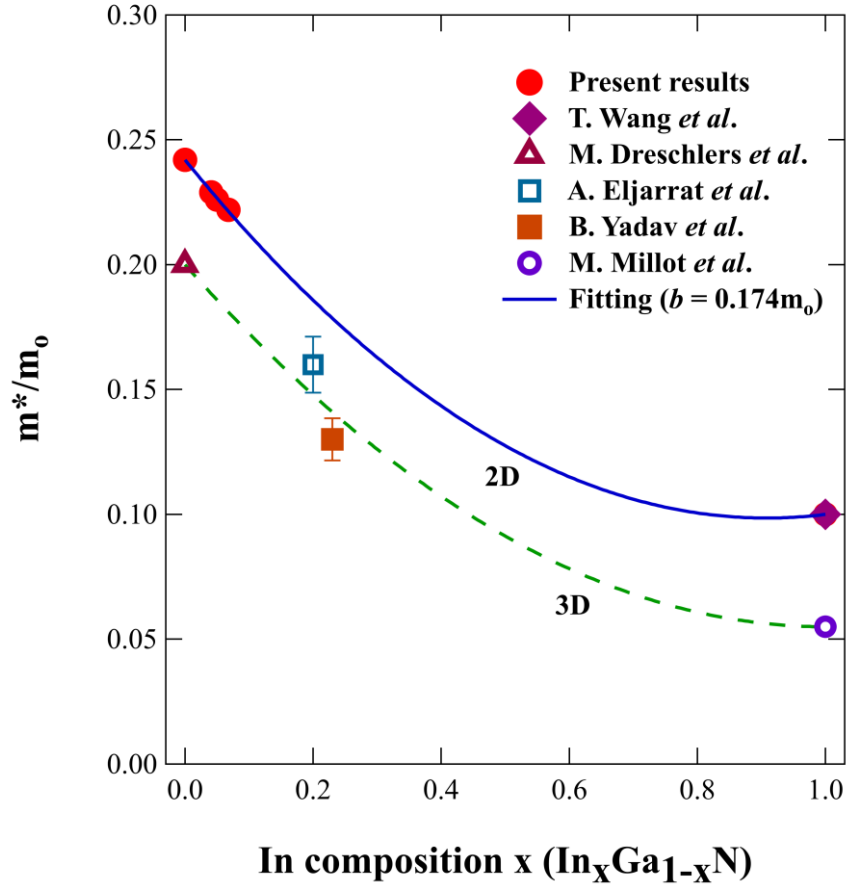


Figure 5.5 Indium composition dependence of the electron effective mass in $\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructures for the whole indium content. The solid circles show the present results, the solid diamond indicates the effective mass of InN 2DES [15], the open triangle indicates bulk GaN [12], the open circle represents the result of bulk InN [65, 66], the solid and open squares show the results of bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$ [67, 68], and solid curve shows a fitting with bowing parameter, $b_m = 0.174 m_0$.

Similar behavior was also observed in the analysis of the indium composition dependence of the bandgap energy of $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloys between $x = 0 \sim 1$. In the case of band-gap energy analysis for similar materials, the bowing behavior showed comparable strong dependence on the indium composition [20, 69, 70]. In addition, such a tendency was also predicted theoretically in the analysis of the effective mass of $\text{In}_x\text{Ga}_{1-x}\text{N}$ alloy up to $x = 1$ %, and the indium composition dependence of the effective mass with bowing behavior was observed [65, 66]. The open triangle and open circle in Figure 5.5 represent the effective mass for bulk GaN and bulk InN (3D system). The effective mass of bulk GaN was determined by Drescher *et al*, in their early study through the CR method. Taking into account the influence of polaron, the mass of GaN was obtained as $m_{\text{GaN}}^* = 0.2m_0$, because GaN has conspicuous large electron-phonon interaction among III-V semiconductors [12].

The electron effective mass in bulk InN was recently determined by SdH oscillation measurements, and further confirmed by magneto-absorption spectroscopy as $m_{\text{InN}}^* = 0.055m_0$. This effective mass parameter was judged to contain strong non-parabolic effect because InN has a narrower band gap energy among III-V nitride semiconductors and small influence from polaron effect [5, 16]. Additionally, the high carrier concentration also accounted for the large band non-parabolicity in their samples. Thus, it is expected that the electron effective mass of $\text{In}_x\text{Ga}_{1-x}\text{N}$ which varies between the mass of GaN and InN has large influence from both the band non-parabolic and polaron effect, and strong dependence on the indium composition.

The solid and open squares in Figure 5.5 represent the effective mass of bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$ that was experimentally obtained recently. Thus far very few studies have been reported both theoretically [65,66] and experimentally [67, 68] the electron effective mass parameter in bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$. The reported experimental mass for bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$ using electrical Hall effect and electron energy loss spectroscopy varies between as $m^* = 0.13 \sim 0.16 m_0$ for $x = 0.05 \sim 0.23$ [67, 68]. Furthermore, the electron effective mass of $\text{In}_x\text{Ga}_{1-x}\text{N}$ was theoretically calculated by various methods such as empirical

tight binding and semi-empirical tight binding, recently. The mass for bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$ between $m^* = 0.2 \sim 0.12 m_0$ for $x = 0 \sim 1$ [67, 68] was estimated. Therefore, from this simple fact from both experimental and theoretical analysis, the mass of $\text{In}_x\text{Ga}_{1-x}\text{N}$ suggests to vary between the mass of GaN and InN.

Using equation (2.2) in chapter two with bowing parameter, $b_m = 0.174m_0$, obtained from the fitting results of the InGaN 2D system, a perfect fitting shown by dashed line (see Figure 5.5) between the bulk GaN (open triangle) and InN (open circle) was obtained. This shows that the bowing parameter, $b_m = 0.174m_0$ can explain perfectly the results of 2D system and the 3D system. Although, at present it is still difficult to obtain high indium content, InGaN 2D systems, it would be interesting to study bowing behaviour in high-indium-content above $x = 6.8\%$ indium content to see if the present assumption can be explained by the present bowing curve..

5.4 Temperature dependence of SdH oscillation

Magneto-transport measurement through the temperature dependence of the SdH oscillation is another method for studying electronic and optical properties of semiconductors. Parameters such as electron effective mass, carrier concentration, Hall mobility and quantum mobility of various semiconductors have been obtained by this method. In SdH oscillation measurements, the oscillations occur because of the conductivity, and thus, magneto-resistance depends on the density of states at the Fermi energy, both through the number of carriers and the scattering time [34, 71, 72].

5.4.1 SdH Oscillation mass

In this work, temperature dependence of the SdH oscillation was carried out at a temperature between $T = 1.5 \sim 30$ K at high magnetic fields up to $B = 15$ T. Figure 5.6 shows temperature dependence of the magneto-resistance for sample with $x = 4.1\%$ indium content. As discussed in

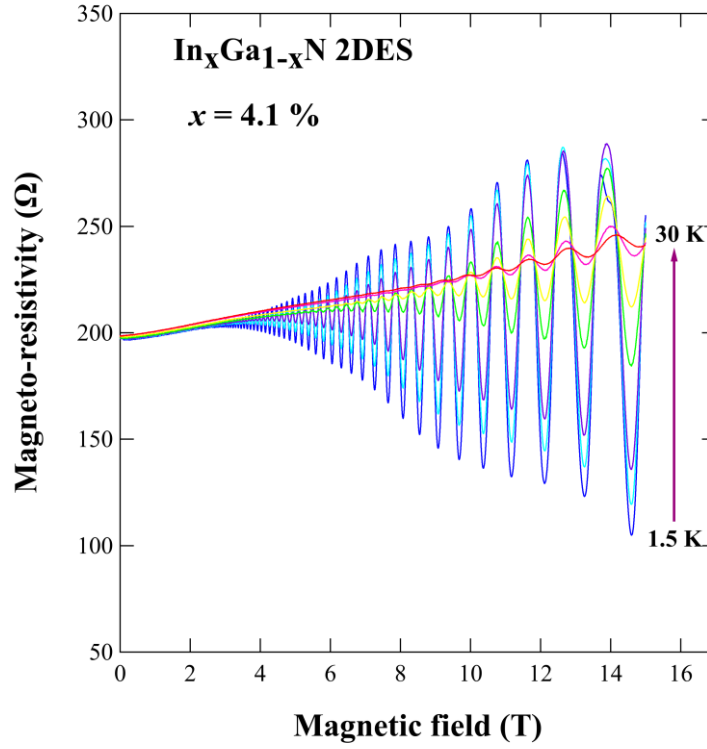


Figure 5.6 Temperature dependence of the magneto-resistivity for sample, $x = 4.1\%$ indium content. The measurement temperature was varied between $T = 1.5 \sim 30$ K with $B = 0 \sim 15$ T.

chapter two, the SdH oscillations grow in amplitude as temperature is lowered because of the enhancement of mobility. At low magnetic fields ($B < 4$ T) decrease in magneto-resistance with increasing magnetic field was observed. With increasing magnetic fields, the periodic SdH oscillations in magneto-resistance are clearly resolved starting with $B = 5$ T. Moreover, the amplitude of the SdH oscillations decreased with increasing temperature due to degradation on sample mobility.

Figure 5.7 shows the SdH oscillation amplitude against inverse magnetic field. This phenomenon indicates that the SdH oscillations are periodic in $1/B$. In 2D electron system where only one sub-band is occupied, the oscillatory part of the magneto-resistivity can be expressed as [33, 71, 72],

$$\rho \propto \frac{\beta T}{B} \exp \left[-\beta \left(\frac{T + T_D}{B} \right) \right] \cos \left(2\pi \frac{h n_s}{2eB} \right). \quad (5.1)$$

Where $\beta = \frac{2\pi^2 k_B m^*}{\hbar e}$, T is experimental temperature, ρ is resistivity, $\hbar$ is reduced Planck's constant and k_B is Boltzmann constant. Equation (5.1) is valid in the case of low magnetic field ($\hbar\omega_c \ll k_B T$).

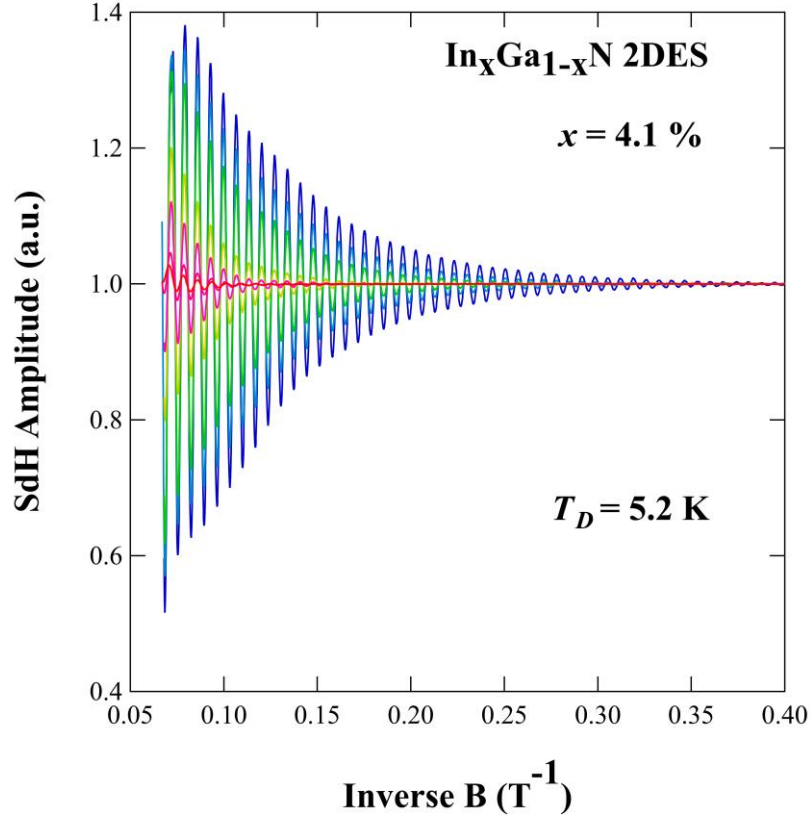


Figure 5.7 Shubnikov–de Haas oscillations against inverse magnetic field. This indicates that the oscillations are periodic in $1/B$. The Dingle temperatures is obtained as 5.2 K from the fitting.

Figure 5.8 shows the temperature dependence of the SdH oscillation amplitude measured at a temperature between $T = 1.5 \sim 30$ K with $B = 0 \sim 15$ T. The SdH oscillation minima were recorded from Figure 5.7 down to 5 T for each spectrum. The effective mass m^* can be derived from the temperature dependence of the SdH oscillation amplitude at the fixed magnetic field using the simplified fitting function [34, 72];

$$\text{Amplitude} \propto \frac{\chi}{\sinh \chi} \quad (5.2)$$

Here, $\chi = \frac{k_B T}{\hbar \omega_c}$. Where T is in Kelvin and magnetic field B in Tesla. A successful fitting procedure was performed on the oscillation amplitude as shown in Figure 5.8, and the effective mass was obtained from the fitting procedure as $m^* = 0.23m_0$. However, it should be noted that equation (5.2) is not necessarily valid in the whole temperature range where the SdH oscillations are observed.

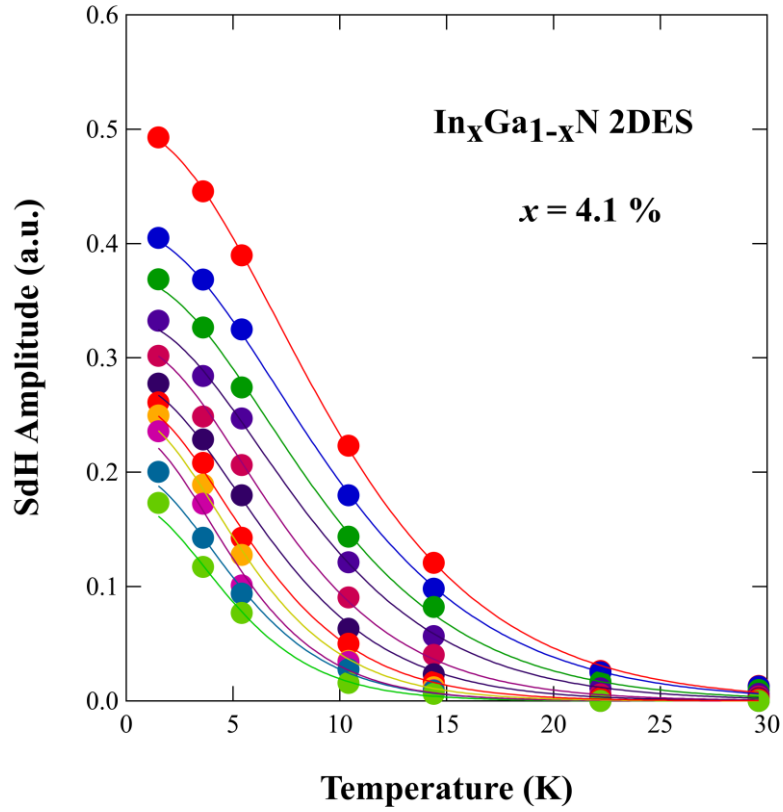


Figure 5.8 Temperature dependence of the SdH oscillation amplitude. The measurement temperatures were varied between $T = 1.5 \sim 30$ K with $B = 0 \sim 15$ T.

Figure 5.9 shows the magnetic field dependence of the effective mass for sample, $x = 4.1\%$

obtained through the fitting procedures in Figure 5.8. The blue solid circle shows SdH mass and red solid circle represents the CR mass. Although SdH oscillation have also been utilized method for obtaining the effective mass of semiconductors, the CR measurement is quite direct and accurate than SdH. The present results show that the CR mass obtained at 13T and 15T are in good agreement with the SdH mass.

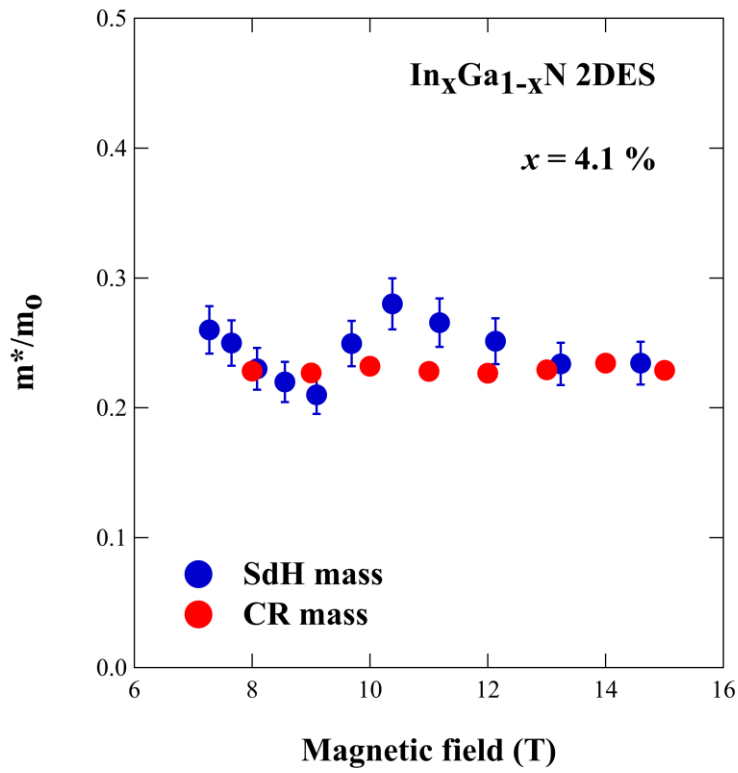


Figure 5.9 Magnetic field dependence of the effective mass for sample, $x = 4.1\%$. The blue solid circle shows SdH mass and red solid circle represents the CR mass.

5.4.2 Scattering mechanism

The performance of electronic devices based on heterostructures is to a large extent depends on the transport properties of the 2D electron systems confined at the interface. This includes the electrons

mobility which also depends on different scattering potentials such as phonon scattering, alloy disorder scattering and interface roughness scattering. So far, various scattering mechanisms limiting the mobility of the 2D electron systems have identified. It has been pointed out that, the CR mobility, quantum mobility and Hall mobility measured in experiments are determined by several different scattering processes and that the common interpretation of the mobility ratio is valid only if all mobilities are dominated by the similar scattering process. To understand the scattering mechanisms in InGaN heterostructures, mobility parameters (CR mobility, quantum mobility and Hall mobility) from both CR and magneto-transport experiment were determined and compared [71, 73].

The quantum mobility can be determined using equation;

$$\mu_q = \frac{\pi}{\beta T_D} \quad (5.3)$$

Where $\beta = \frac{2\pi^2 k_B m^*}{\hbar e}$. Using $T_D = 5.2$ K, the quantum mobility is obtained as $1,600 \text{ cm}^2/\text{V}\cdot\text{s}$. This value is by a factor of three smaller than the CR mobility ($4,400 \text{ cm}^2/\text{V}\cdot\text{s}$) which was obtained from the CR line-width in Figure 5.1 (a), and is almost two times smaller than the Hall mobility ($3,400 \text{ cm}^2/\text{V}\cdot\text{s}$) which was estimated from magneto-transport experiments in chapter two. In addition, the Hall mobility is slightly closer to the CR mobility. The small discrepancy between them can be attributed to the broadening of the CR line-width as a result of various scattering events. Such discrepancy between the CR mobility and Hall mobility was also investigated in high carrier concentration AlGaIn/GaN heterostructures. The electron-electron interaction and inhomogeneity of the sample was pointed as the major reason [73].

5.5 Conclusions

In summary, cyclotron resonance measurements were carried out in $\text{In}_x\text{Ga}_{1-x}\text{N}$ heterostructures with indium composition ranging between; $x = 0 \sim 7 \%$, at a temperature, $T = 1.7\text{K}$. The absorption spectra were clearly observed for each magnetic field up to $B = 15\text{T}$, and the effective mass was

obtained from the fitting. The CR absorption and effective mass in InGaN 2DES are firstly observed in this dissertation. The obtained effective mass varies gradually with increasing indium composition, and the indium composition dependence of the effective mass shows bowing behavior. The bowing parameter between GaN ($x = 0$) and InN ($x = 1$) end materials was obtained as $b_m = 0.174m_0$. This bowing tendency is in good agreement with recent study on the band gap energy of similar materials for whole indium composition. Moreover, the bowing parameter can explain perfectly the effective mass variation of bulk $\text{In}_x\text{Ga}_{1-x}\text{N}$ for the entire indium composition, $x = 0 \sim 1$.

Cyclotron mass obtained from the CR measurements were found to be in good agreement with the one obtained from temperature dependence of the Shubnikov-de Haas oscillation. This is the first determination of the effective mass in InGaN 2DES from both measurements as far as it is known.

Three different mobilities, namely; cyclotron mobility, quantum mobility and Hall mobility have been obtained and compared based on the scattering mechanisms such as alloy disorder, interface roughness and phonon.

CHAPTER SIX

Results and Discussion

InGaAs/InAlAs Heterostructures

6.1 Introductory statement

InGaAs is a narrow gap semiconductor which has the potential for application to spintronic devices because of its large spin-orbit interaction. The InGaAs semiconductor is one of the good candidates for probing structure induced spin-splitting energy, known as, the Rashba effect. However, Rashba effect was mainly estimated through the beat pattern analysis and the fast Fourier transform analysis in the Shubnikov-de Haas (SdH) oscillation [10, 11]. Cyclotron resonance (CR) is also a powerful tool for the direct observation of the spin splitting energy. In addition, the application of high magnetic field can exceed various excitation energies which allows to study new phenomena in semiconductors.

In this chapter, CR experiments were performed in an inverted InGaAs/InAlAs heterostructures in order to investigate Rashba spin-splitting energy and effective mass at high magnetic field. The inclusion of Rashba term tends to modify the Landau levels. Hence, because of Rashba effect the CR splitting is expected in the absorption spectra [44].

6.2 Magneto-transport results

Figure 6.1 shows magnetic field dependence of magneto-resistance and Hall resistance at high magnetic fields up to 27 T generated by hybrid magnet at a temperature, $T = 1.7\text{K}$. The SdH oscillation and the quantum Hall plateau were observed clearly at the integer filling factor. Using similar analysis which was discussed in the chapter four and five, the mobility and the carrier concentration was obtained as $\mu = 20 \text{ m}^2/\text{V}\cdot\text{s}$ and $n_s = 5.8 \times 10^{11} \text{ cm}^{-2}$, respectively. The InGaAs sample has very high mobility, hence, SdH oscillation and plateaus starts to show up at low magnetic field in comparison to

the previous samples discussed in chapter four and five (GaN and InGaN 2DES).

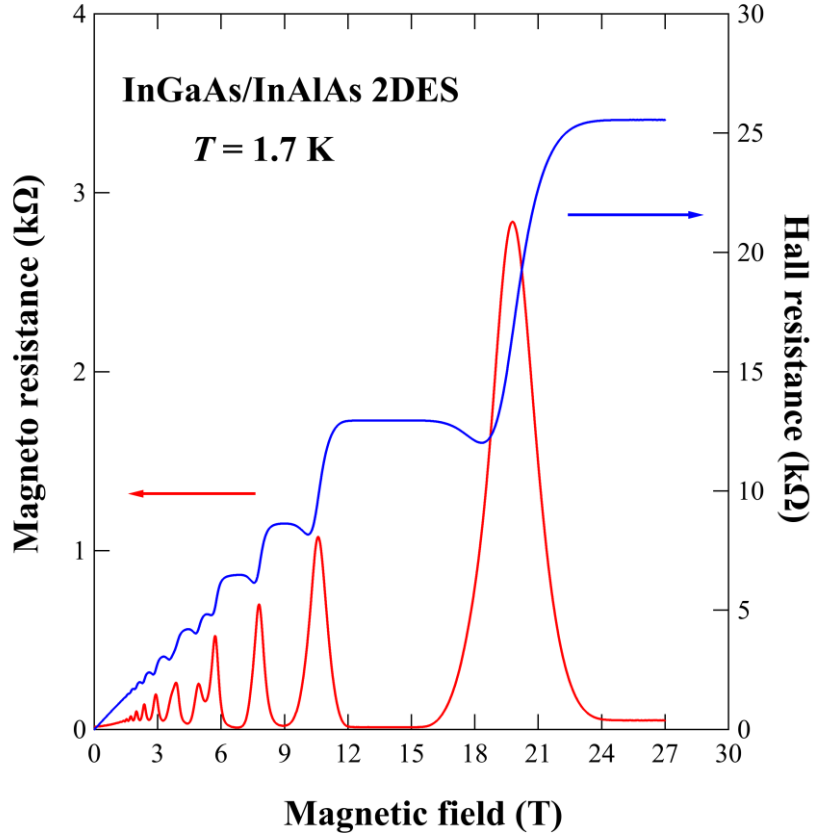


Figure 6.1 Typical magneto-transport data for inverted InGaAs/InAlAs heterostructures at high magnetic fields up to 27 T at 1.7 K (hybrid magnet was used).

6.3 CR results and discussion

Figure 6.2 shows the magnetic field dependence of the CR spectra taken between $B = 1.5$ and 9 T at $T = 1.7$ K. The single resonant absorption was clearly observed for each magnetic field up to $B = 7.5$ T, and the resonance shifts to the higher energy with increasing magnetic field (see Figure 6.2 (a)). The blue solid curves in Figure 6.2 (a) show the fitting results with the standard Lorentzian curve. The precise resonant energy and width can be obtained from the curve fitting procedure. However, above

7.5T satellite peaks appeared and becomes pronounced with increasing magnetic fields, in particular at 9T as revealed in Figure 6.2 (b). The resonance with satellite peaks were perfectly fitted using double Lorentz curve. The satellite peak is probably because of Rashba effect.

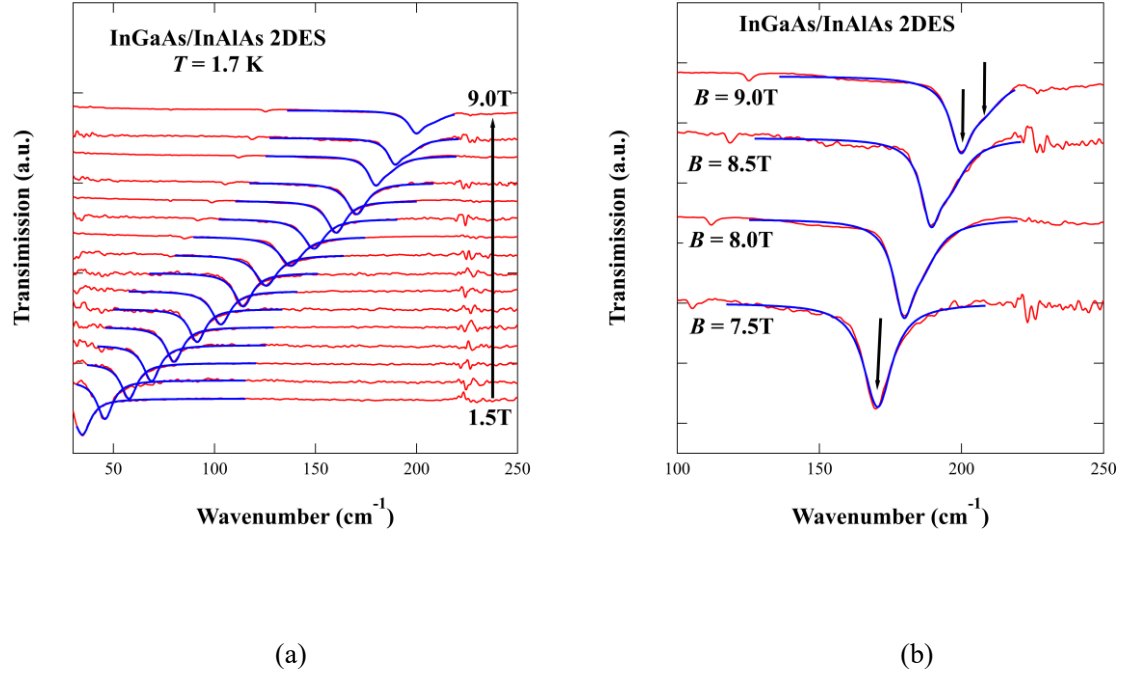


Figure 6.2. Magnetic field dependence of CR transmission spectra for the inverted InGaAs heterostructures. (a) CR spectra between 1.5 T and 9 T. (b) High magnetic field spectra with B between 7.5 T and 9 T at $T = 1.7$ K.

Magnetic field dependence of the resonant energy is shown in Figure 6.3. The solid circles denote the present CR results. The lines represent the CR transition with Rashba term which was calculated using equation (2.79) from chapter two. The CR splitting from the satellite peaks were clearly observed. The calculated lines with Rashba term are in good agreement with CR splitting at high magnetic field region [11, 47]. This confirms that the satellite peaks are probably due to by Rashba effect.

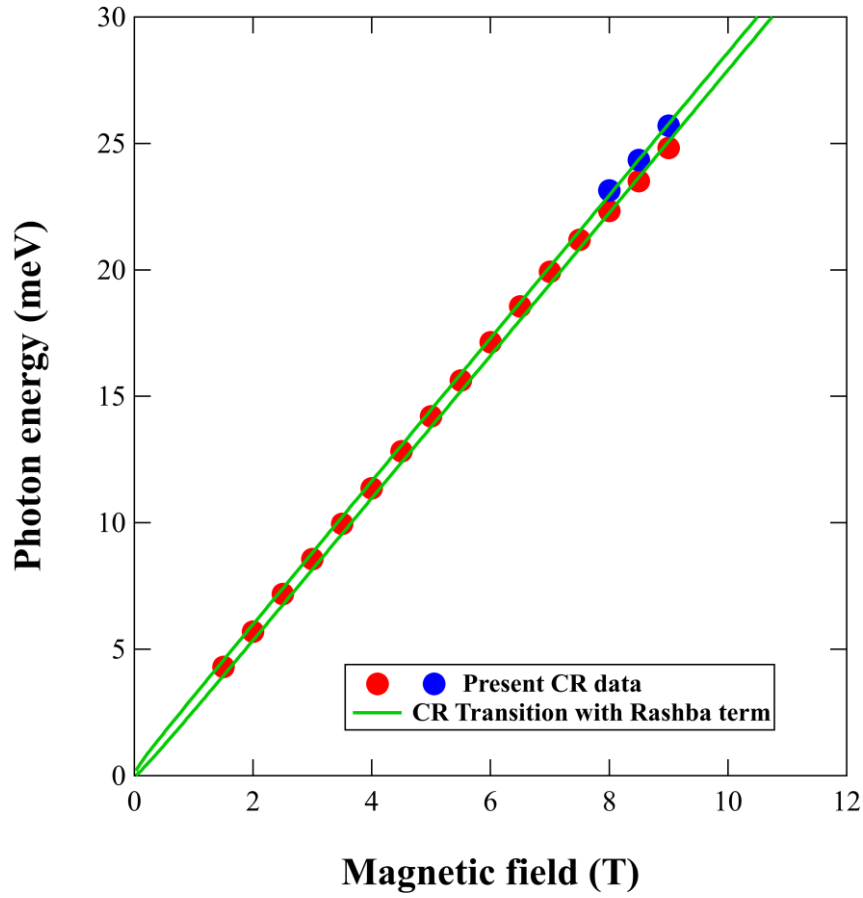


Figure 6.3 Magnetic field dependence of the CR energy between 1.5T and 9T. The blue solid circles shows the CR energy from satellite peaks.

The summary of the CR absorption spectra and energy at high magnetic field above 9T is shown in Figure 6.4. The lines indicating transverse-optical (TO) phonon and the longitudinal-optical (LO) phonon energy for $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}$ are also shown. The intensity of the resonant peaks (Marked with A in Figure 6.4 (a)) was found to decrease with increasing magnetic fields, and disappear around the TO-phonon energy. Multiple absorption resonances (Marked with B and C in Figure 6.4 (a)) which vanishes at higher magnetic fields were also observed. There was no transmission signal above 250 cm^{-1} (see table 6.1) because of absorption from GaAs substrate.

Furthermore, in Figure 6.4 (b) anomalous anti-crossing of the CR line was observed in the vicinity of the TO-phonon energy. Such anti-crossing of the CR line usually can be found around LO-phonon energy, and is commonly known as resonant polaron effect. In the vicinity just above LO-phonon energy the observed mass becomes very small because of the resonant effect. As the CR energy is further increased, the observed mass tends to approach the bare electron mass [74]. As discussed in chapter two, for standard resonant polaron effect, as the CR energy approaches LO-phonon energy, the effective mass becomes heavier, until the energy curve is flattened when the CR energy is equal to LO-phonon energy. At higher frequency range, there appears another branch, where the observed mass is smaller than polaron mass [42]. This situation is very similar to the effective mass behavior shown in Figure 6.5. However, in the present results, anti-crossing of the CR line occurred at TO-phonon energy instead of LO-phonon energy.

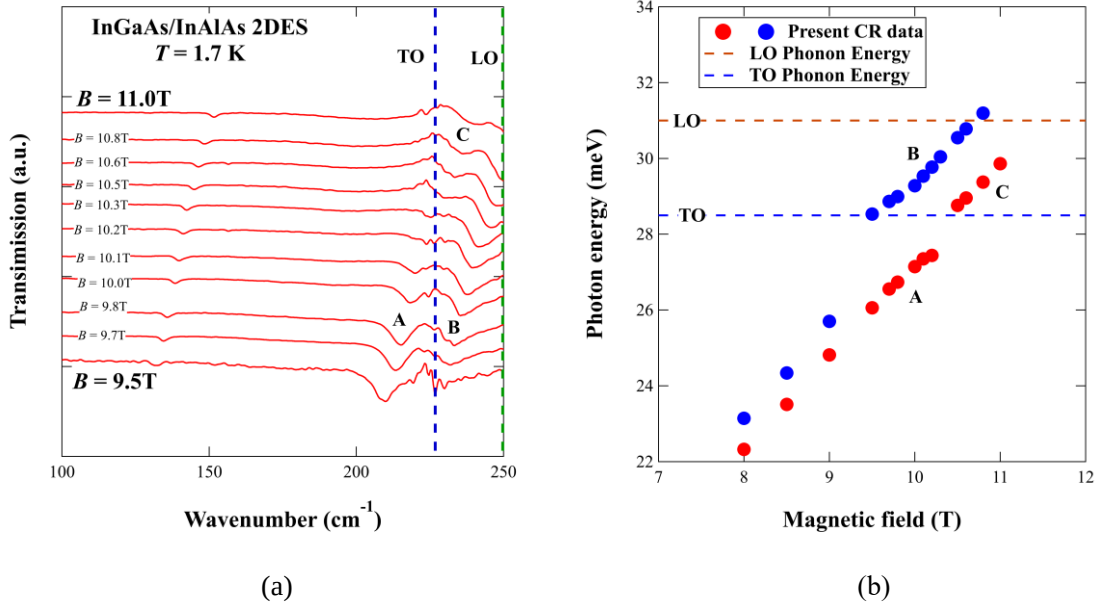


Figure 6.4. Magnetic field dependence of the (a) CR spectra, and (b) CR energy for InGaAs heterostructures.

In order to find the origin of the observed anti-crossing of the CR line, detailed investigation of other CR experiments in 2DES was carried out. In the case of CdTe/CdMgTe quantum wells, Karczewski *et al* [74], found anti-crossing of the CR line in the vicinity of LO-phonon energy. Since, CdTe has large electron–phonon interaction with LO–phonon coupling constant ($\alpha = 0.3$), they concluded that such anti-crossing of the CR line is due to the resonant polaron effect. However, this is not similar to the present anti-crossing of the CR for the present sample.

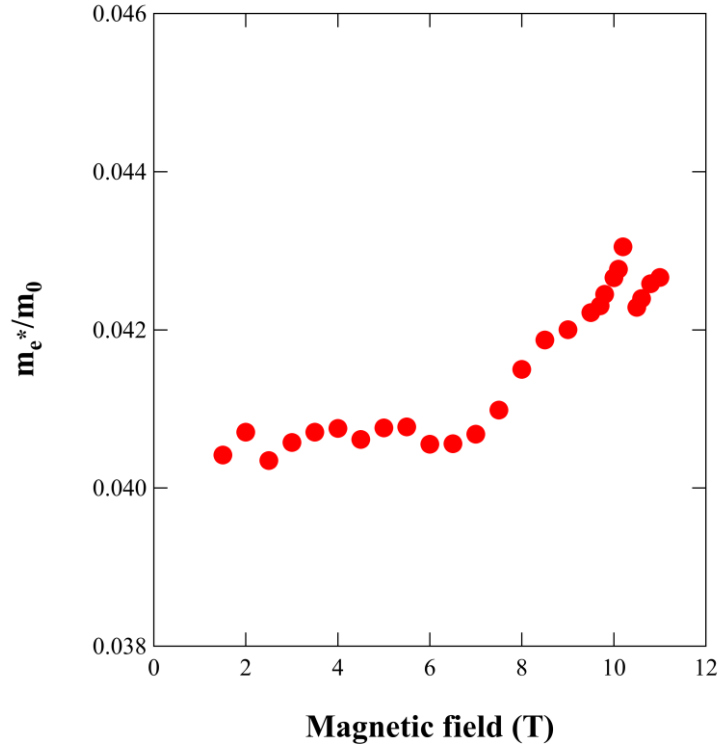


Figure 6.5. Magnetic field dependence of the effective mass for InGaAs heterostructures showing drastic change of the effective mass at high magnetic fields.

Furthermore, similar unexpected anti-crossing of the CR line was also experimentally observed in high carrier density GaAs quantum well by Poulter *et al* [75] and Faugeras *et al* [76] in their attempt to investigation of resonant polaron effect quantum well system. The anti-crossing of the CR line

around the TO-phonon energy was explained through the formation of new of the CR excitation which has energy close to the TO-phonon energy, and this behavior tends to be evidence in case of high carrier density quantum well. It was theoretically predicted that anti-crossing can occur around TO-phonon energy in the case of high carrier density samples [77]. This is because in high carrier density there exist longitudinal modes with frequency close to TO-phonon energy which are active in CR.

Table 6.1 Phonon frequency in some compound semiconductors discussed here [12-14].

	InAs	GaAs	In _{0.75} Ga _{0.25} As	CdTe
LO	7.16 THz (239 cm ⁻¹)	8.55 THz (285 cm ⁻¹)	7.50 THz (250 cm ⁻¹)	5.08 THz (169 cm ⁻¹)
TO	6.52 THz (217 cm ⁻¹)	8.02 THz (267 cm ⁻¹)	6.90 THz (230 cm ⁻¹)	4.20 THz (140 cm ⁻¹)
α	0.052	0.068	0.056	0.29

This new mode which has energy close to TO-phonon energy is originally formed due to coupling between LO-phonon energy and plasma frequency. Such a mode can couple with CR energy resulting into anti-crossing of the CR line in the vicinity of TO-phonon energy. This assumption was applied to the experimental results of high-density GaAs quantum well, and it could explain the results perfectly. The new mode was named as magnetoplasmon-phonon. From this result it was confirmed and concluded that in high-density systems, magnetoplasmon-phonon mixing is the major reason for the anti-crossing of the CR line in the vicinity of TO-phonon frequency rather than LO-phonon frequency.

Through qualitative theoretical analysis and comparison with present data, it was concluded that such modes could be the reason for the CR splitting in the vicinity of TO-phonon energy in present

data. However, more experiments for several InGaAs samples with different carrier density is needed in future to finally confirm these theoretical arguments. In addition, the drastic increase of the effective mass at high magnetic field is also attributed to this new mode.

6.4 Conclusions

CR measurements of inverted InGaAs/InAlAs heterostructure have been performed. Single CR absorption was clearly observed at low magnetic field region, and satellite peaks appeared with increasing magnetic fields. The satellite peaks are probably caused by the Rashba effect because InGaAs has the larger spin-orbit interaction among narrow gap semiconductors. The satellite peaks were found to be in good agreement with the calculation of Landau levels with Rashba effect.

Large enhancement of the effective mass was observed at high magnetic field close to transverse optical (TO) phonon energy. Additional multiple resonances appear at higher magnetic fields below and above TO-phonon energy, and large drastic change of the effective mass was observed.

Moreover, anomalous anti-crossing of the CR line in the vicinity of TO-phonon energy rather than LO-phonon frequency was observed for the first time in InGaAs 2DES. This is attributed to new mode with the energy close to TO-phonon energy which can appear in case of high density 2DES.

CHAPTER SEVEN

Summary

7.1 Conclusions

Cyclotron resonance experiments in AlGa_N/Ga_N, AlGa_N/InGa_N and inverted InGaAs/InAlAs heterostructures have been investigated at high magnetic fields. The summary of the measurement results for all the systems have been provided as follows.

In AlGa_N/Ga_N heterostructure, the CR absorption was clearly observed at each magnetic field. The obtained effective mass of the 2D electron was found to increase with increasing both magnetic field and carrier density. The mass enhancement has been discussed in details from the viewpoint of polaron effect because Ga_N has a large electron-LO-phonon interaction among III-V compounds, and the band non-parabolicity due to high carrier concentration variation. Through separating the contribution from the polaron effect and the band non-parabolicity, it is concluded that the 2D electron mass in Ga_N heterostructures is strongly affected by the dense carrier density. This result, has finally solved the contradiction in relation to the widely reported value of the effective mass in Ga_N 2DES.

In addition, the magnetic field dependence of the electron mobility in the Ga_N 2DES is found to decrease gradually with increasing magnetic field. This is mainly due to the variation of electron scattering time through the broadening of the Landau levels because of the short-range scattering.

In the case of AlGa_N/In_{*x*}Ga_{1-*x*}N heterostructures ($x = 0 \sim 7\%$), cyclotron absorption spectra were clearly observed for each magnetic field for the first time. The obtained effective mass varies gradually with increasing indium composition. The indium composition dependence of the effective mass showed bowing behavior. The bowing mass between Ga_N ($x = 0$) and InN ($x = 1$) end materials was obtained as $b = 0.174m_0$. This bowing tendency is in good agreement with recent study on the bandgap energy of similar materials for the whole indium content. Moreover, the bowing mass can explain perfectly the effective mass variation of bulk In_{*x*}Ga_{1-*x*}N for the entire range of indium composition.

The CR mass obtained from the CR measurements were found to be in good agreement with that obtained from temperature dependence of the Shubnikov-de Haas oscillation. This is the first observation of the effective mass in InGaN 2D electron systems from both measurements.

For inverted InGaAs/InAlAs heterostructure, single CR absorption was clearly observed at low magnetic field region, and with increasing magnetic fields, satellite peaks appeared. The satellite peaks are related to Rashba effect because InGaAs has the larger spin-orbit interaction among narrow gap semiconductors. In addition, the satellite peaks were found to be in good agreement through the calculation of Landau levels with Rashba effect.

The effective mass was obtained as $m^* = 0.04m_0$ at low magnetic field region. however, large enhancement was observed at high magnetic field close to transverse optical (TO) phonon energy. Additional multiple resonances appear at higher magnetic fields below and above TO-phonon energy, and large drastic change of the effective mass was observed. Moreover, anomalous anti-crossing of the CR line in the vicinity of TO-phonon energy rather than longitudinal optical-phonon frequency was observed for the first time in InGaAs 2D electron system. The anti-crossing of the CR line and drastic change of the effective mass was explained from the view point of the magneto-plasmon phonon mode in high carrier density heterostructure systems.

7.2 Future works

1. Theoretical simulation is needed for justification of the assumption of effective longitudinal optical coupling constant in GaN 2D electron system.
2. Detailed cyclotron resonance in high indium content InGaN heterostructures are needed in future to justify the validity of the bowing mass at wider range of indium composition.
3. More experiments for several InGaAs samples with different carrier densities are needed in future to finally confirm theoretical assumption of the magneto plasmon-phonon mode.

References

1. K. von Klitzing, “*The quantized Hall effect*”, Rev. Mod. Phys. **58**, 519 (1986).
2. H. L. Störmer, “*The fractional quantum Hall effect*”, Rev. Mod. Phys. **71**, 875 (1999).
3. D. C. Tsui, “*Interplay of disorder and interaction in two-dimensional electron gas in intense magnetic fields*”, Rev. Mod. Phys. **71**, 891 (1999).
4. D. C. Tsui, H. L. Stormer and A. C. Gossard, “*Two-Dimensional Magneto transport in the Extreme Quantum Limit*”, Phys. Rev. Lett. **48**, 1559 (1982).
5. H.Y. Hwang, Y. Iwasa, M. Kawasaki, B. Keimer, N. Nagaosa, and Y. Tokura, “*Emergent phenomena at oxide interfaces*”, Nat. Mater, **11**, 103 (2012).
6. O. Ambacher, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, W. J. Schaff, L. F. Eastman, R. Dimitrov, L. Wittmer, M. Stutzmann, W. Rieger and J. Hilsenbeck, “*Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaIn/GaN heterostructures*”, J. Appl. Phys. **85**, 3222 (1999).
7. I. Vurgaftman, and J. R. Meyer “*Band parameters for Nitrogen-containing semiconductors*”, J. Appl. Phys. **94**, 3675 (2003).
8. L. Sang, M. Liao, Y. Koide and M. Sumiya, “*InGaN-based thin film solar cells: Epitaxy, structural design, and photovoltaic properties*”, J. Appl. Phys. **117**, 105706 (2015).
9. I. Zutic, J. Fabian, and S. Das Sarma, “*Spintronics: Fundamentals and applications*”, Rev. Mod. Phys., **76**, (2004).
10. S. Yamada, S. Nitta, H. Iwase, M. Akabori, Y. Imanaka and T. Takamasu, “*Magnetic field dependency of spin-splitting in $In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As$ two-dimensional electron gas with strong Rashba spin-orbit coupling*”, J. Phys.: Conf. Ser. **334**, 012063 (2011).
11. J. Nitta, T. Akazaki, H. Takayanagi and T. Enoki, “*Gate Control of Spin-Orbit Interaction in an Inverted $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ Heterostructure*”, Phys. Rev. Lett. **78**, 1335 (1997).

12. M. Drechsler, D. M. Hofmann, B. K. Meyer, T. Detchprohm, H. Amano and I. Akasaki, “*Determination of the conduction band electron effective mass in hexagonal GaN*”, Jpn. J. Appl. Phys. **34**, L1178 (1995).
13. B. F. Spencer, W. F. Smith, M. T. Hibberd, P. Dawson, M. Beck, A. Bartels, I. Guiney, C. J. Humphreys, and D. M. Graham, “*Terahertz cyclotron resonance spectroscopy of an AlGaN/GaN heterostructure using a high-field pulsed magnet and an asynchronous optical sampling technique*”, Appl. Phys. Lett. **108**, 212101 (2016).
14. S. Syed, J. B. Heroux, Y. J. Wang, M. J. Manfra, R. J. Molnar, and H. L. Stormer, “*Nonparabolicity of the conduction band of wurtzite GaN*”, Appl. Phys. Lett. **83**, 4553 (2003).
15. T. Wang X. Wang, Z. Chen, X. Sun, P. Wang, X. Zheng, X. Rong, L. Yang, W. Guo, D. Wang, J. Cheng, X. Lin, P. Li, J. Li, X. He, Q. Zhang, M. Li, J. Zhang, X. Yang, F. Xu, W. Ge, X. Zhang, and B. Shen. “*High-Mobility Two-Dimensional Electron Gas at InGaN/InN Heterointerface Grown by Molecular Beam Epitaxy*”, Adv. Sci. **5**, 1800844 (2018).
16. F. Iacopi, M. V. Hove, M. Charles, and K. Endo, “*Power electronics with wide bandgap materials: Toward greener, more efficient technologies*”, MRS Bull. **40**, 390 (2015).
17. V. M. Mitin, V. A. Kochelap, and M. A. Strocio, “*Quantum Heterostructures: Microelectronics and Optoelectronics*”, Cambridge University Press, Cambridge, (1999).
18. O. Madelung, “*Semiconductors: Data Handbook*”, Springer, Berlin, Heidelberg (2003).
19. T. Zhu and R. A. Oliver, “*Unintentional doping in GaN*”, Phys. Chem. Chem. Phys. **14**, 9558 (2012).
20. I. Vurgaftman, J. R. Meyer and L. R. Ram-Mohan, “*Band parameters for III–V compound semiconductors and their alloys*”, J. Appl. Phys. **89**, 0021 (2001).
21. B. Rezaei, A. Asgari, and M. Kalafi, “*Electronic band structure pseudopotential calculation of wurtzite III-nitride materials*”, Phys. B **371**, 107 (2006).

22. A. De and C. E. Pryor, “*Predicted band structures of III-V semiconductors in the wurtzite phase*”, Phys. Rev. B **81**, 155210 (2010).
23. Y. A. Du, S. Sakong, and P. Kratzer, “*As vacancies, Ga antisites, and Au impurities in zinc blende and wurtzite GaAs nanowire segments from first principles*”, Phys. Rev. B **87**, 075308 (2013).
24. A. R. Denton and N. W. Ashcroft, “*Vegard's law*”, Phys. Rev. A **43**, 3161 (1991).
25. J. M. Luttinger and W. Kohn, “*Motion of Electrons and Holes in Perturbed Periodic Fields*”, Phys. Rev. **97**, 4 (1955).
26. M. G. Burt, “*The justification for applying the effective-mass approximation to microstructures*”, J. Phys. Condens. Matter **4**, 6551 (1992).
27. J. Callaway, “*Energy band theory*” (Academic Press, New York, London) (1964).
28. M. J. Kelly, “*Low dimensional semiconductors*”, Clarendon Press, Oxford, (1995)
29. C. Kittel, “*Introduction to Solid State Physics*”, 8th edition (2005).
30. P. Drude, “*On the electron theory of metals*”, Annalen Der Physik, **1**, 566 (1900).
31. C. Hamaguchi, “*Basic semiconductor physics*”, 2th edition (2010).
32. G. Dresselhaus, A. F. Kip, and C. Kittel, “*Cyclotron Resonance of Electrons and Holes in Silicon and Germanium Crystals*”, Phys. Rev. **98**, 368 (1955).
33. A. B. Fowler, F. F. Fang, W. E. Howerd and P. J. Stiles, “*Magneto-Oscillatory Conductance in Silicon Surfaces*”, Phys. Rev. Lett. **16**, 901(1966).
34. T. Ando, AB. Fowler and F. Stern, “*Electronic properties of two-dimensional systems*”, Rev. Mod. Phys. **54**, 437 (1982).
35. Jr. Allen, D. C. Tsui and J. V. Dalton, “*Far-Infrared Cyclotron Resonance in the Inversion Layer of Silicon*”, Phys. Rev. Lett. **32**, 107 (1974).
36. G. Abstreiter, P. Kneschanrek, J. Kotthaus and JF. Koch, “*Cyclotron Resonance of Electrons in an Inversion Layer on Si*”, Phys. Rev. Lett. **32**, 104 (1974).

37. G. Abstreiter, J. Kotthaus, J. F. Koch and G. Dorda, “*Cyclotron resonance of electrons in surface space-charge layers on silicon*”, Phys. Rev. **14**, 2480 (1976).
38. W. Kohn, “*Cyclotron Resonance and de Haas-van Alphen Oscillations of an Interacting Electron Gas*”, Phys. Rev. **123**, 1242(1961).
39. M. L. Sadowski, G. Martinez, M. Potemski, C. Berger, W. A. De Heer and C. Lepes, “*Magneto-spectroscopy of epitaxial graphene*”, Intern. J. Modern. Phys. B **21**, 1145 (2007).
40. M. A. Hopkins, R. J. Nicholas, M. A. Brummel, J. J. Harris and C. T. Foxon, “*Cyclotron-resonance study of nonparabolicity and screening in GaAs/Ga_{1-x}Al_xAs heterojunctions*”, Phys. Rev. B **36**, 4789 (1987).
41. J. T. Devreese, “*Polarons*”, Appl. Phys. **14**, 383 (1996).
42. R. J. Nicholas, M. Watts, D. F. Howell, F. M. Peeters, X. Wu, J. T. Devreese, L. van Bockstal, F. Herlach, C. J. G. M. Langerak, J. Singleton and A. Chevy, “*Cyclotron resonance of both magnetopolaron branches for polar and neutral optic-phonon coupling in the layer compound InSe*”, Phys. Rev. B **45**, 12144 (1992).
43. F. M. Peeters and J. T. Devreese, “*Energy levels of two- and three-dimensional polarons in a magnetic field*”, Phys. Rev. B **31**, 3689 (1985).
44. Y. Imanaka, T. Takamasu, S. Nitta and S. Yamada, “*Cyclotron resonance of two dimensional Rashba systems in InGaAs*”, J. Phys.: Conf. Ser. **334** 012061 (2011).
45. B. Das, S. Datta and R. Reifengerger, “*Zero-field spin splitting in a two-dimensional electron gas*”, Physica. Rev. B **41**, 8278 (1990).
46. Y. Sato, T. Kita, S. Gozu, and S. Yamada, “*Large spontaneous spin splitting in gate-controlled two-dimensional electron gases at normal In_{0.75}Ga_{0.25}As/In_{0.75}Al_{0.25}As heterojunctions*”, J. Appl. Phys., **89**, 8017 (2001).
47. K. Fujii, Y. Morikami, T. Ohyama, S. Gozu and S. Yamada, “*Determination of Rashba spin*

- splitting in $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Al}_{1-y}\text{As}$ by far-infrared magneto-optical absorption*”, *Physica E* **12**, 432 (2002).
48. N. Perea-Lopez, J. Tao, J. B. Talbot, J. McKittrick, G. A. Hirata and S. P. DenBaars, “*A novel hybrid pulsed laser deposition/metalorganic vapour deposition method to form rare-earth activated GaN*”, *J. Phys. D: Appl. Phys.* **41**, 122001 (2008).
 49. J. Raúl, M. Palma and A. Lakhtakia, “*Chapter 15 -Vapor-Deposition Techniques*”, *J. Engineered Biomimicry*, 383 (2013).
 50. S. Gozu, C. Hong and S. Yamada, “*Low Temperature High Electron Mobility in $\text{In}_{0.75}\text{Ga}_{0.25}\text{As}/\text{In}_{0.75}\text{Al}_{0.25}\text{As}$ Modulation-Doped Heterostructures Grown on GaAs Substrate*”, *Jpn. J. Appl. Phys.* **37** L1501(1998).
 51. A. Munajad, C. Subroto and S. Uwarno, “*Fourier Transform Infrared (FTIR) Spectroscopy Analysis of Transformer Paper in Mineral Oil-Paper Composite Insulation under Accelerated Thermal Aging*”, *Energies*, **11**, 364 (2018).
 52. Y. Zong and R. U. Datla, “*Development of a Bolometer Detector System for the NIST High Accuracy Infrared Spectrophotometer*”, *J. Res. Natl. Inst. Stand. Technol.* **103**, 605 (1998).
 53. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Terahertz Cyclotron Resonance in AlGaIn/GaN Heterostructures*”, *J. Korean Phys. Soc.* **74**, 159 (2019).
 54. W. Knap, S. Contreras, H. Alause, C. Skierbiszewski, J. Camassel, M. Dyakonov, J. L. Robert, J. Yang, Q. Chen, M. Asif Khan, M. L. Sadowski, S. Huant, F. H. Yang, M. Goiran, J. Leotin, and M. S. Shur, “*Cyclotron resonance and quantum Hall effect studies of the two-dimensional electron gas confined at the GaN/AlGaIn interface*”, *Appl. Phys. Lett.* **70**, 2123 (1997).
 55. J. Singleton, R. J. Nicholas, D. C. Rogers, and C. T. B. Foxon “*Cyclotron resonance of electrons in a narrow GaAs/(Ga,Al)As quantum well: polaron effects and non-parabolicity*”, *Sur. Sci.* **96**, 429 (1988).

56. W. Knap, H. Alause, J. M. Bluet, J. Camassel, J. Young, M. Asif Khan, Q. Chen, S. Huant and M. S. Shur, “*The cyclotron resonance effective mass of two-dimensional electrons confined at the GaN/AlGaN interface*”, Sol. Stat. Comm. **99**, 195 (1996).
57. O. Madelung, “*Semiconductors: Data Handbook*”, Springer, Berlin, Heidelberg (2003).
58. V. M. Mitin, V. A. Kochelap, and M. A. Strocio, “*Quantum Heterostructures: Microelectronics and Optoelectronics*”, Cambridge University Press, Cambridge, (1999).
59. X. Wu and F. M. Peeters, “*Cyclotron-resonance mass of two-dimensional electrons in GaN/Al_xGa_{1-x}N heterostructures*”, Phys. Rev. B **55**, 15438 (1997).
60. Y. Imanaka and N. Miura, “*Polaron cyclotron resonance and impurity effects in II-VI semiconductors at ultra-high magnetic fields up to 210 T*”, Physica B **201**, 284 (1994).
61. P. Voisin, Y. Gulder, J. P. Vieren, M. Voos, P. Delescluse and N. T. Linh, “*Cyclotron resonance linewidth in selectively doped GaAs/Al_xGa_{1-x}As heterojunctions*”, Appl. Phys. Lett. **39**, 982 (1981).
62. M. Sumiya, D. Kindole, K. Fukuda, S. Yashiro, K. Takehana, T. Honda, and Y. Imanaka, “*Growth of AlGaN/InGaN/GaN Heterostructure on AlN Template/Sapphire*”, Phys. Status. Solidi. B **1900524**, 1900524-1 (2020).
63. N. Armakavicius, V. Stanishev, S. Knight, P. Kuhne, M. Schubert and V. Darakchieva, “*Electron effective mass in In_{0.33}Ga_{0.67}N determined by mid-infrared optical Hall effect*”, Appl. Phys. Lett. **112**, 082103 (2018).
64. F. C-P. Massabuau, P. Chen, M. K. Horton, S. L. Rhode, C. X. Ren, T. J. O ’Hanlon, A. Kovacs, M. J. Kappers, C. J. Humphreys, R. E. Dunin-Borkowski and R. A. Oliver, “*Carrier localization in the vicinity of dislocations in InGaN*”, J. Appl. Phys. **121**, 013104 (2017).
65. M. Millot, N. Ubrig, J. M. Poumirol, I. Gherasoiu, W. Walukiewicz, S. George, O. Portugall, J. L’etot, M. Goiran and J. M. Broto, “*Determination of effective mass in InN by high-field oscillatory magnetoabsorption spectroscopy*”, Phys. Rev. B **83**, 125204 (2011).

66. M. Goiran, M. Millot, J. M. Poumirol, I. Gherasoiu, W. Walukiewicz, and J. Leotin, “*Electron cyclotron effective mass in indium nitride*”, Appl. Phys. Lett. **96**, 052117 (2010).
67. A. Eljarrat, L. L. Conesa, C. Magen, N. G. Lepetit, Z. Gacevic, E. Calleja, F. Peiro and S. Estrade, “*Quantitative parameters for the examination of InGaN QW multilayers by low-loss EELS*”, Phys. Chem. Chem. Phys. **18**, 23264 (2016).
68. B. S. Yadav, P. Mohanta, R. S. Srinivasa and S. Major, “*Electrical and optical properties of transparent conducting $In_xGa_{1-x}N$ alloy films deposited by reactive co-sputtering of GaAs and indium*”, Thin Sol. Fil. **555**, 179 (2014).
69. G. Orsal, Y. El Gmili, N. Fressengeas, J. Streque, R. Djerboub, T. Moudakir, S. Sundaram, A. Ougazzaden and J.P. Salvestrini, “*Bandgap energy bowing parameter of strained and relaxed InGaN layers*”, Opt. Mat. Exp. **4**, 1032 (2014).
70. G. Franssen, I. Gorczyca T. Suski, A. Kaminska, J. Pereiro, E. Muñoz, E. Iliopoulos, A. Georgakilas, S. B. Che, Y. Ishitani, A. Yoshikawa, N. E. Christensen, and A. Svane, “*Bowing of the band gap pressure coefficient in $In_xGa_{1-x}N$ alloys*”, J. Appl. Phys. **103**, 033514 (2008).
71. A. Wolos, W. Jantsch, K. Dybko, Z. Wilamoswski and C. Skierbiszewski, “*Plasmon-cyclotron resonance in two-dimensional electron gas confined at the GaN/AlGaN interface*”, Phys. Rev. B **76**, 045301 (2007).
72. S. Yamada and T. Makimoto, “*Subband mobility of quasi-two-dimensional electrons in Si atomic layer doped GaAs*”, Appl. Phys. Lett. **57**, 1022 (1990).
73. S. Syed, M. J. Manfra, Y. J. Wang, R. J. Molnar and H. L. Stormer, “*Electron scattering in AlGaN/GaN structures*”, Appl. Phys. Lett. **84**, 1507 (2004)
74. G. Karczewski, T. Wojtowicz, Y. Wang, X. Wu and F.M. Peeters, “*Electron Effective Mass and Resonant Polaron Effect in CdTe/CdMgTe Quantum Wells*”, Phys Stat Sol (b) **229**, 597 (2002).
75. A. J. L. Poulter, J. Zeman, D. K. Maude, M. Potemski, G. Martinez, A. Riedel, R. Hey, and K. J.

- Friedland, “*Magneto-infrared Absorption in High Electron Density GaAs Quantum Wells*”, Phys. Rev. Lett. **86**, 336 (2001).
76. C. Faugeras, C. Faugeras, G. Martinez, A. Riede, R. Hey, K. J. Friedland, and Yu. Bychkov, “*Fröhlich Mass in GaAs-Based Structures*”, Phys. Rev. Lett. **92**, 107403 (2004).
77. S. N. Klimin and J. T. Devreese, “*Cyclotron resonance of an interacting polaron gas in a quantum well: Magnetoplasmon-phonon mixing*”, Phys. Rev. B **68**, 245303 (2003).

Journal Publications, Conferences, Symposiums, Meetings and Seminars

The results presented in this research work have been published in various journals and presented at several international conferences, domestic meetings/forums, symposiums and seminars as shown in the following lists.

List of Journal Publications

- i. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Terahertz Cyclotron Resonance in AlGa_N/Ga_N heterostructures*”, J. Korean Phys. Soc. **74**, 159 (2019).
- ii. M. Sumiya, D. Kindole, K. Fukuda, S. Yashiro, K. Takehana, T. Honda, and Y. Imanaka, “*Growth of AlGa_N/InGa_N/Ga_N Heterostructure on AlN Template/Sapphire*”, Phys. Status. Solidi. B **1900524**, 1900524-1 (2020).
- iii. D. Kindole, Y. Imanaka, K. Takehana, and M. Sumiya, “*Cyclotron resonance and magneto-transport in InGa_N heterostructures*”. (2020): **To be submitted**

List of International Conferences and Symposiums

- i. M. Sumiya, D. Kindole, K. Fukuda, S. Yashiro, K. Takehana, T. Honda, and Y. Imanaka, “*Direct Growth of AlGa_N/InGa_N/Ga_N Structure on AlN Template for Measurement of Effective Mass in InGa_N Layer*”, The 13th International Conference on Nitride Semiconductors (ICNS-13) (2019).
- ii. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Polaron Cyclotron Resonance in AlGa_N/Ga_N Heterostructures*”, The 34th International Conference on the Physics of Semiconductors (ICPS-34) (2018).
- iii. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Terahertz Cyclotron Resonance in AlGa_N/Ga_N heterostructures*”, The 19th International Symposium on the Physics of Semiconductors and Applications (ISPSA-19) (2018).

List of Domestic conferences, Symposiums, Meetings and Seminars

- i. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Carrier concentration dependence of cyclotron resonance in AlGa_N/Ga_N heterostructure*”, The 74th Japan SP Annual Meeting, 14pE201-5 (2019).
- ii. Y. Imanaka, D. Kindole, K. Takehana, S. Yamada and S. Nitta, “*Cyclotron resonance in InGaAs 2DES in the vicinity of optical phonon energy*”, The 74th JSP Autumn Meeting, 10aD15-3 (2019).
- iii. M. Sumiya, D. Kindole, K. Fukuda, S. Yashiro, K. Takehana, T. Honda, and Y. Imanaka, “*Electron transport at the interface of AlGa_N/InGa_N fabricated on AlN template*”, The 30th Anniversary Symposium, Materials Research Society of Japan, (2019).
- iv. D. Kindole, Y. Imanaka, K. Takehana, and M. Sumiya, “*Cyclotron Resonance in In_xGa_{1-x}N/AlGa_N Heterostructures*”, The 74th JSP Autumn Meeting, 10aD15-2 (2019).
- v. M. Sumiya, D. Kindole, K. Fukuda, S. Yashiro, K. Takehana, T. Honda, and Y. Imanaka, “*Growth of AlGa_N/InGa_N heterostructure grown on AlN template for cyclotron resonance measurement*”, The 80th Japan Society of Applied Physics (JSAP) Autumn Meeting (2019).
- vi. D. Kindole, Y. Imanaka, K. Takehana, L. Sang, M. Sumiya and S. Yamada, “*Cyclotron Resonance in Quantum Hall Systems*”, NIMS Advanced Measurement and Characterization Symposium (ACMP), P37 (2019).
- vii. Y. Imanaka, D. Kindole, K. Takehana, L. Sang and M. Sumiya, “*Effective Mass in InGa_N two-dimensional electron systems*”, The 80th Japan Society of Applied Physics (JSAP) Autumn Meeting (2019).
- viii. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Cyclotron Resonance in AlGa_N/Ga_N Heterostructures at High Magnetic Fields II*”, The 73th JSP Annual Meeting, 23pPSA-28 (2018).

- ix. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Terahertz Cyclotron Resonance in GaN heterostructure*”, NIMS Joint Symposium on Materials Integration and Advanced Materials Characterization (ACMP), P58 (2018).
- x. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Cyclotron Resonance and Magneto-transport Studies in InGaN/GaN Heterostructures*”, The 73th JSP Autumn Meeting, 11pPSA-17 (2018).
- xi. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Cyclotron resonance in GaN quantum Hall systems*”, High Magnetic Field forum, P30 (2017).
- xii. D. Kindole, Y. Imanaka, K. Takehana, L. Sang and M. Sumiya, “*Cyclotron resonance in AlGaIn/GaN heterostructures at high magnetic fields*”, The 72th JSP Autumn Meeting, 21pPSA-35 (2017).

Acknowledgement

I wish to express my utmost gratitude to my supervisor, Professor Yasutaka Imanaka, who guided me in this research work from the proposal to the final stage. His guidance, provision of basic knowledge on physics of semiconductors, suggestions, advice and constructive comments have been invaluable. Special acknowledgement to Dr. Kanji Takehana and Dr. Giyuu Kido of National Institute for Materials Science (NIMS), Japan, for their guidance experimental set up and advice for obtaining useful data, and Dr. Masatomo Sumiya of NIMS for supplying GaN and InGaN samples.

Furthermore, I would wish to express my sincere appreciation to Prof. Syoji Yamada of Osaka Institute of Technology, Japan, for supplying InGaAs samples and his invaluable advice. Prof. Ki-Seok AN of Korean Research Institute of Chemical Technology and the University of Science and Technology, Korea, for his constructive information on semiconductors. Special thanks to Prof. Emeritus Hiroyasu Nakata of Osaka Kyoiku University, Japan for his discussion on physics of semiconductors, and for providing me with the guidance for the preparation of this dissertation.

I thank Hokkaido University for granting me a gracious opportunity to study and conduct research at NIMS. Indeed, the program has been very useful and invaluable to me. I am also indebted to the NIMS graduate program for granting me research stipend. I assure you that the resources you have spent for my education will add value to your commitment to ensure technical and managerial competency in development issues and strengthen the relationship between Japan and Tanzania.

I thank Ms. Yasuko Yamazaki, a personal secretary for my professor, for the support on issues related to administration and her great guidance on social related matters in Tsukuba city. I also thank other group members; Dr. Matsumoto, and Dr. Takezwa for their engagement.

Lastly, I extend my deep and sincere appreciation to my lovely family at large, especially, my wife Julieth Danfred and my daughter Dorcas for the love, encouragement and support for the entire period I was engaged in the study program.