GaN/AlN Multiple Quantum Wells and Nitride-Based Waveguide Structures for Ultrafast All-Optical Switch Utilizing Intersubband Transition

サブバンド間遷移超高速全光スイッチに向けた
GaN/AlN 多重量子井戸及び窒化物系導波路構造に関する研究

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by

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ABSTRACT

Intersubband transition (ISBT) in multiple quantum wells (MQW) has drawn much attention for ultrafast optoelectronic devices owing to its wide wavelength-tunability and extremely fast energy relaxation process. Recently, the extension of ISBT wavelength to near-infrared wavelength, especially 1.55 μm, is of particular interest because such wavelength is vital for the development of ultrafast photonic devices for silica-fiber-based optical-communication networks. Among various materials proposed for intersubband transition at 1.55 μm, GaN/AlN MQW structures are promising due to their large conduction band offset of approximately 2 eV. Furthermore, the large electron effective mass and the large LO phonon energy in nitrides make their intersubband relaxation extremely fast in the order of sub-picoseconds. This makes intersubband transition in nitrides immensely interesting for the development of ultrafast photonic devices operating at a bit rate higher than 1 Tb/s.

The intersubband transition at 1.55 μm and shorter wavelengths have been achieved by molecular beam epitaxy (MBE) with the shortest wavelength of 1.08 μm. On the other hand, growth by metalorganic vapor phase epitaxy (MOVPE) has not yielded satisfactory results as the shortest ISBT wavelength reported is merely 2.4 μm. The demonstration of 1.55-μm ISBT by MOVPE, however, is still attractive since much better crystalline quality for device fabrication can be achieved. Moreover, MOVPE also has another advantage over MBE in industrial point of view. Indeed, the ultrafast optical switching utilizing intersubband transition has been demonstrated by MBE-grown GaN ridge waveguide structure with a bit rate higher than 1 Tb/s. However, such device requires optical-pulse switching energy higher than 10 pJ/μm^2 to utilize the saturable intersubband absorption, which is still too large for the applications in conventional optical communication networks. Reduction of the switching energy is therefore another important issue for the intersubband transition devices. In order to reduce the switching energy, not only the waveguide fabrication process, but also the epitaxial growth technique and the device structure have to be improved.

In this dissertation, the GaN/AlN multiple quantum wells and nitride-based

waveguide structures are studied and fabricated for the applications of ultrafast all-optical switch utilizing intersubband transition. The ultrafast intersubband transition device is realized by using AlN waveguide structure with GaN/AlN quantum wells. This AlN-waveguide-based intersubband transition device can operate in the optical communication wavelength range, covering 1.3 μm, the shortest wavelength ever demonstrated for the intersubband transition devices.

In order to perform epitaxial growth of such structure with high quality, MOVPE is more preferable than MBE because the AlN layer can be grown with much better quality by the MOVPE. However, since the MOVPE growth of GaN/AlN MQW for the 1.55-μm ISBT is very difficult, the AlN waveguide structure was fabricated with a combination of both MOVPE and MBE growth techniques: MOVPE growth for AlN buffer layer and MBE re-growth for GaN/AlN multiple quantum wells. With this combination, the high quality waveguide with intersubband absorption in a wavelength range of 1.3-1.55 μm is achieved.

In addition to the improvement in the epitaxial growth technique, this dissertation also discusses on the problems in growing the waveguide structure of both MOVPE and MBE. Moreover, the design and fabrication of nitride-based waveguide structures are studied in details to improve the waveguide quality. The high-optical-confinement waveguide structures are proposed and successfully fabricated for the first time thanks to the successful demonstration of epitaxial growth and the improvement of fabrication process. Additionally, a new waveguide characterization method using the supercontinuum light source is also proposed and demonstrated. With this new characterization method, not only are the direct measurements of intersubband absorption in waveguides realized, but the problems in waveguide quality of the MBE-grown waveguide are also revealed. This provides very useful information for the improvement of fabrication process, especially the epitaxial growth process. The achievements in each area of epitaxial growth, waveguide fabrication process, and characterization, have made contributions to the improvement of waveguide characteristic, leading to the successful demonstration of the first AlN-waveguide-based intersubband transition devices with high performance.

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 Background

The rapid and global spread of the Internet has created the need for data communication systems which can process an enormous quantity of data at a very high speed. This accelerates the growth of silica-fiber-based optical communication networks due to its high capabilities that satisfy the high demands for the bandwidth in the data transmission. The photonic networks based on Wavelength Division Multiplexing (WDM) and Optical Time Division Multiplexing (OTDM) are the key technologies to achieve an ultra-high-speed transmission in the optical communication systems to deal with an extreme large amount of data. Along with the development of these core networks, the development of ultrafast optical devices for the ultra-high-speed all-optical signal processing to support the networks is indispensable.

Nevertheless, by the present technology of which most of optical devices utilize the *interband transition* (transition of electrons between valence band and conduction band), including electro-absorption (EA) modulators [1-6], Mach-Zehnder interferometer [7-20], and fiber-based devices [21-29], the speed of all-optical signal processing is limited by the carrier lifetime of electrons between conduction and valence bands. Therefore, the demonstration of all-optical signal processing at a bit rate over 640 gigabit-per-second (Gbps, a billion of bits per second) by such devices has been still unsuccessful. One of the keys to the invention of novel ultra-high-speed optical devices is the utilization of *intersubband transitions* (transition of electrons or holes between energy levels in the same conduction band or valence band) in quantum wells (QWs) [30-35]. Its unique properties such as wide range of transition-wavelength tunability have been applied for the design and fabrication of many kinds of application in mid-infrared and far-infrared wavelength regime, for example, Quantum Well Infrared Photodetector (QWIP) [36-41] and Quantum Cascade Laser [42-52]. Moreover, its ultrafast energy relaxation time has drawn much attention for novel optical devices such as ultrafast all-optical switches [53-64], since it is expected that the optical devices operating at ultra-high-speed on the order of terabit-per-second (Tbps, a trillion of bits per second) can be achieved by the utilization of this extremely fast relaxation time [65-76]. The realization of the intersubband transition at a wavelength of 1.55 μm, the most important wavelength for silica-fiber based optical communication networks, is therefore vital for the development of optical communication networks.

In order to realize the intersubband transition at 1.55 μm, the quantum well structure with a large conduction band offset between well and barrier is required. The multiple quantum well (MQW) structures of many material systems including InGaAs/AlAs [77,78], InGaAs/AlAsSb [79,80], GaN/Al(Ga)N [81-93] and ZeSe/BeTe [94-97] are proposed due to their large conduction band offset of more than 1.3 eV. Among such material systems, one of the most interesting systems in realizing the intersubband transition in optical communication wavelength regime is GaN/Al(Ga)N system because of its large conduction band offset of approximately 2 eV. With this large conduction band offset, a wide range of intersubband transition from mid-infrared to near-infrared wavelength regime has been demonstrated. The realization of intersubband absorption at 1.55 μm was firstly demonstrated by Gmachl *et al.* using GaN/AlGaN MQW structure [85]. After that, the success on the growth of GaN/AlN MQW structure has demonstrated that the large conduction offset of nitride-based quantum wells is promising to obtain the intersubband absorption at 1.55 μm and shorter wavelengths as the shortest wavelength reported is 1.08 μm [88,89]. Furthermore, high LO phonon scattering rate in GaN made its energy relaxation time faster than that of other material systems. It was demonstrated that the intersubband relaxation time in the GaN/AlN MQW structures is the shortest among other material systems, less than 150 fs at 4.5 μm [71], and 160 fs at 1.55 μm [73]. It is thus expected that the all-optical switches utilizing the intersubband transitions in nitride-based quantum wells can operate at a very high bit rate on the order of terabit-per-second.

1.2 Interband and Intersubband Transition

In a quantum well, which consists of a thin semiconductor layer of the order of 100 Å embedded in a semiconductor with two semiconductor materials, both electrons and holes can be confined in one direction in the allowed energy levels that satisfies the Schrödinger equation. This quantum confinement leads to the quantization of energy levels, and the formation of subbands in quantum wells and superlattice structures as illustrated in Fig. 1.1. Both electrons and holes have their own subband energy levels. The subbands for electrons and holes exist above the conduction band and below the valence band, respectively. The term "interband transition" describes the transition of electrons between the valence band and the conduction band. The interband transition is the most well known phenomenon of the semiconductors as their electrical properties can be changed with excitation of electrons from the valence band to the conduction band; The semiconductors act as insulator at 0 K, while their electrical conductivities are much improved with thermal or optical excitation. The interband transition could therefore be said that it is the fundamental principle of semiconductor optical devices. With this principle, many optical devices have been developed, for example, photo detectors [98-102], light emitting diodes (LED) [103-106], laser diodes (LD) [107-111].

The term "intersubband transition" describes the transition of electrons or holes between subband energy levels within the same conduction band or valence band. The intersubband transition is therefore sometimes called as "intraband transition" because the transitions occur within a conduction band or valence band. The most common intersubband transition, however, concerns the transition of electrons between subband energy levels of the conduction band. This is because band energy and wave function of the conduction band is much easier to study compared to those of the valence band. Additionally, the mobility of electrons is higher than that of holes, meaning that faster optical devices can be obtained by the intersubband transition within conduction band. The conduction-band intersubband-transition is therefore more interesting and is widely studied for the device fabrication. Since the intersubband transition utilizes only conduction (or valence) band, the energy of transition is normally smaller than that of interband transition. Therefore, its applications are mostly for the optical devices in mid-infrared and far-infrared wavelength range. The interband transition and intersubband transition are shown schematically in figure 1.1.

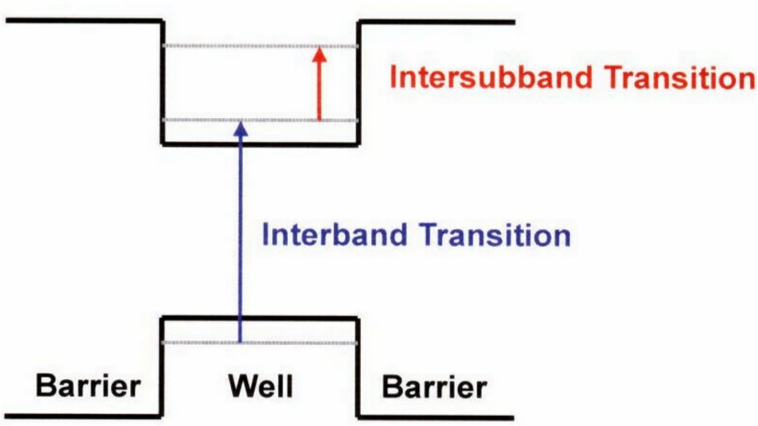

Figure 1.1 Interband and Intersubband Transitions

1.3 Characteristics of Intersubband Transition

One of the interesting characteristics of the intersubband transition is "wavelength tunability". The energy levels of each subband in a quantum well can be calculated by solving the Schrödinger equation. It is known that the energy of intersubband transition is a function of quantum well thickness. In other words, the intersubband transition energy (or wavelength) can be tuned by only changing the quantum well thickness without changing composition of materials in the quantum structure. This characteristic has made the utilization of intersubband transition being a good scheme to realize optical devices in the mid-infrared to far-infrared wavelength range, which is essentially difficult to be achieved by interband transition.

Another interesting characteristic of the intersubband transition is "ultrafast energy relaxation". The energy relaxation of an electron when it is excited to high subband energy level is considered to be governed by the Fröhlich interaction between the electron and longitudinal optical (LO) phonon [112]. Figure 1.2 shows a schematic diagram of intersubband and intrasubband transition by LO phonon scattering. The energy of intersubband transition is independent of the electron wave vector parallel to the well ($k_{//}$). Therefore, intersubband absorption is mainly determined by the number of electrons populating the lowest subband, irrespective of their kinetic energy. When an electron relaxes to the first subband energy level by LO phonon scattering, it relaxes to a high kinetic energy region of that subband. The intersubband energy after the relaxation process is less than the energy before the excitation. Therefore, it cannot re-absorb the pumped light if it does not relax to bottom region of subband, the area of

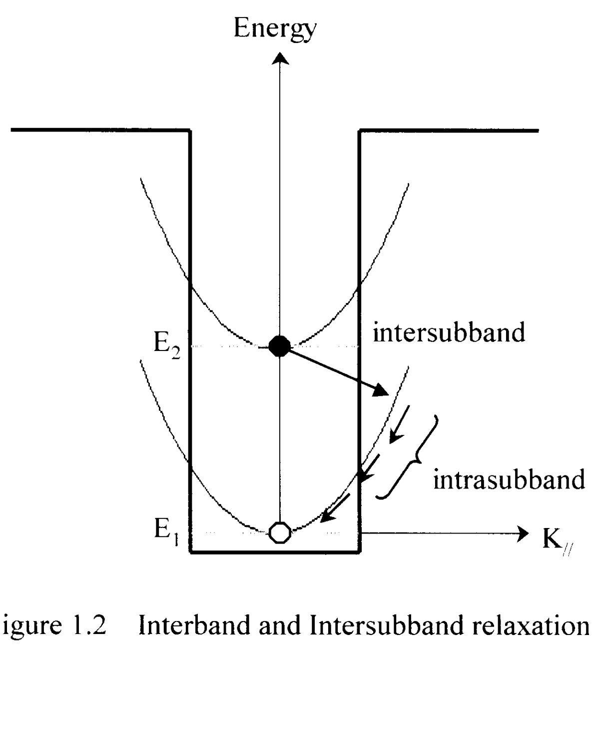

Figure 1.2 Interband and Intersubband relaxation

which the intersubband energy is so high that it is re-excited by the pumped light. The relaxation time of this process is thus approximately equal to the sum of the time spent for both the intersubband relaxation and the intrasubband relaxation [113-115]. Therefore, in order to relax to the bottom region of the subband, an electron requires many LO phonons for the intrasubband relaxation process. In other words, the higher the energy of intersubband transition, the larger the number of LO phonons necessary for the process, consequently slowing down the relaxation process in case of high energy intersubband transition.

Adopting the guided-mode model to depict LO phonons confined in the quantum well, the intersubband scattering rate of an electron at the bottom of the second subband can be calculated by the following equation [112].

$$W_{21} = \frac{1}{2} W_0 \left(\frac{\hbar\omega_{LO}}{E_1} \right)^{\frac{1}{2}} \left[\frac{1}{4 - (\hbar\omega_{LO}/E_1)} + \frac{1}{12 - (\hbar\omega_{LO}/E_1)} \right] \qquad (1.1)$$

Here, W_0 refers to the basic scattering rate, which is given by

$$W_0 = \frac{e^2}{4\pi\hbar} \left(\frac{2m^*\omega_{LO}}{\hbar} \right)^{\frac{1}{2}} \left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_s} \right) \qquad (1.2)$$

where $\hbar$ is Planck's constant divided by 2π;

ω_{LO} is the angular frequency of LO phonons;

E_1 is the energy of the lowest subband;

m^* is the effective mass; and ε_∞ and ε_s are the optical permittivity and the static dielectric permittivity, respectively.

With these characteristics, the intersubband transition has been developed to be an excellent device mechanism for ultrafast optical switches due to its extremely fast relaxation time of the order of picosecond, which is three orders of magnitude shorter than the carrier life time. Particularly, the intersubband transition in nitride semiconductor QWs is of great interest since the relaxation time is in the order of sub-picosecond, shorter by an order of magnitude than that of other semiconductors [71-74].

1.4 Optical Devices Based on Intersubband Transition

1.4.1 Quantum well infrared photodetector

Quantum well infrared photodetector (QWIP) utilizes the photo-excitation of electrons (or holes) between the subband energy levels in the conduction (or valence) band of quantum wells. The quantum well structure is designed so that these photo-excited carriers can escape from the quantum well and be collected as photocurrent with external bias voltage, as schematically shown in Fig. 1.3. QWIP affords greater flexibility than extrinsically doped semiconductor infrared detectors because the wavelength of the peak response and cutoff can be continuously tailored by varying quantum well thickness and barrier composition. QWIP has been developed for many kinds of application, including QWIP camera which can detect even the far infrared (> 8 μm). QWIP camera makes the wider visible range for human, and it has been used in various fields of study, including volcanology, medicine, fire-fighting and astronomy [33, 34].

QWIPs can be fabricated by widely used semiconductors such as GaAs. Therefore, they have many advantages compared with MCT detectors, including the mature growth and processing technologies of materials. QWIPs can be grown with high uniformity, excellent reproducibility, large-area, and also low-cost. Additionally, the ability to accurately control the band structure, and hence spectral response, allows monolithically

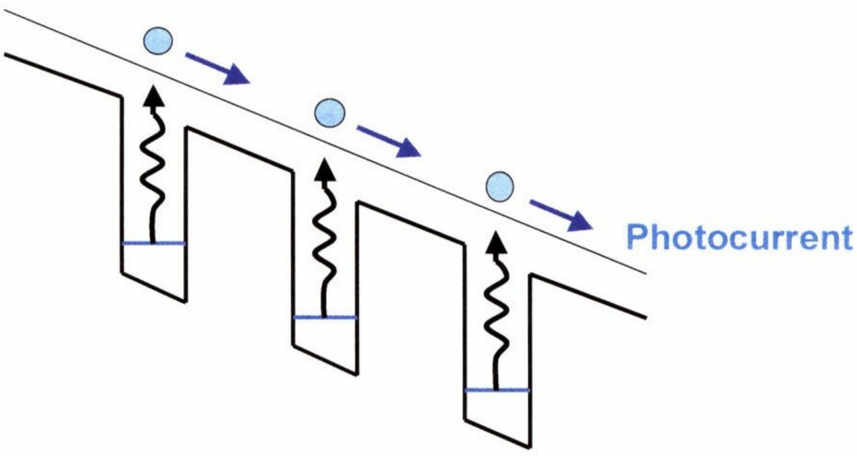

Figure 1.3 Schematic diagram of quantum well infrared photodetector

integrated multi-spectral infrared detectors as well as the potential for monolithic integration with high-speed GaAs multiplexers and other electronic devices.

1.4.2 Quantum cascade laser

The quantum cascade (QC) laser is a new semiconductor laser based on intersubband transitions. In general, the generation of photons by intersubband transitions is a very difficult task because of the fast competing non-radiative relaxation through the emission of optical phonons. In the QC lasers, this problem is overcome by careful engineering of the band structure, which can be divided to 2 main parts: active region and injection region. The "active region" is designed to have many subband energy levels or minibands, for example, 3-energy-level structure as illustrated in Fig. 1.4. In order to create the condition of population inversion, the transition time of electrons between bottom levels (2→1) must be much shorter than the transition time between the top to bottom (3→2), which can be achieved by carefully designing the quantum structure. In the "injection region", there is an important part namely "energy filter" which is designed to block electrons that exist on the top of the active region, while electrons after making transition to lower state of the active region can pass through this filter part to "injector". Finally, the electrons are effectively utilized through the injection to the next stage of QC laser by the injector part.

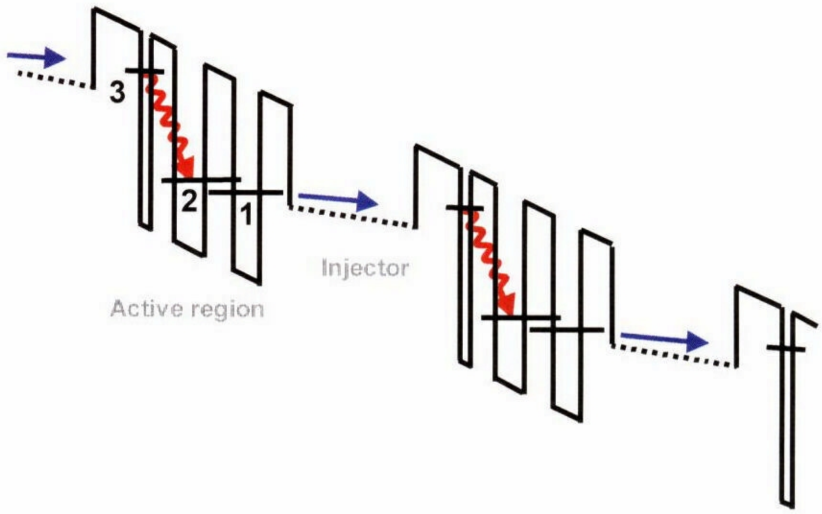

Figure 1.4 Schematic diagram of a quantum cascade laser

Many quantum structures have been demonstrated to achieve good characteristic of QC lasers [42-51], leading to the realization of QC lasers operating at room-temperature [51]. Because the QC laser utilizes the intersubband transition, the lasing wavelength can be tailored by designing the quantum structures, i.e. well and barrier width, using the same heterostructure materials. The QC laser therefore became an important candidate for the fabrication of long wavelength lasers. They offer the potential advantage, compared with conventional semiconductor lasers, such as lead-salt-based structures, of better reliability and yields. They can also cover the infrared spectrum with much wider gap materials, such as AlGaAs/GaAs, InP/GaInAs, and AlInAs/GaInAs, which are inherently more robust, easy to process and less prone to detect formation than narrow-band gap semiconductors. This enables the achievement of QC lasers in wide wavelength-range from mid-infrared (3~8 μm)[46], far-infrared region (>8 μm)[47], and microwave region (>50μm) [48,49].

1.4.3 Ultrafast all-optical switch

Another intersubband transition device that has been attracting much attention recently is "ultrafast all-optical switch". Such all-optical switch is expected to be extremely fast on the order of terabit per second (Tb/s), since it would be realized by the utilization of the ultrafast intersubband relaxation. Moreover, the wide range of wavelength-tunability led to another possibility to obtain these devices with the operation wavelength around 1.55 μm, the silica-fiber-based optical communication wavelength, being ready for the application in future optical communication networks. There are two modulation schemes to utilize the intersubband absorption for all-optical switch.

1) Modulation of interband transition by intersubband transition

In this modulation scheme, three subbands, including first valance subband (VB1), first conduction subband (CB1) and second conduction subband (CB2), are used as schematically shown in Fig. 1.5. Since CB1 is full of electrons, Interband resonant light absorption (VB1→CB1) is usually saturated at a level, making the interband resonant light pass through the device with almost no absorption. However, such absorption can be increased by exciting the electrons from CB1 to CB2 using Intersubband-resonant

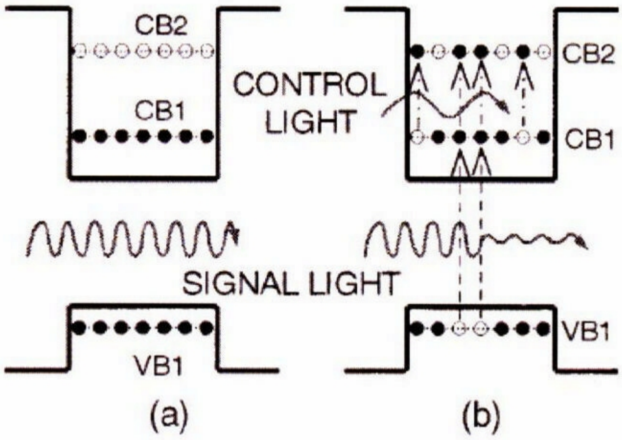

Figure 1.5 Modulation of Interband transition by Intersubband transition:
(a) ON state, (b) OFF state

light, inducing large absorption of interband resonant light which is "off" state. The interband absorption decreases and returns to "on" state, when the electrons relax from CB2 to CB1, with very fast speed owing to the ultrafast intersubband relaxation. This scheme could therefore modulate the signal with recovery time as short as 1 ps [53].

2) Modulation of intersubband transition by intersubband transition

Although the last scheme shows very high modulation speed, the wavelength of signal pulse is still not applicable to the 1.55-μm optical communication networks since the interband resonant wavelength is usually much shorter than 1.55 μm, while long intersubband resonant wavelength is required. To utilize the device in the optical

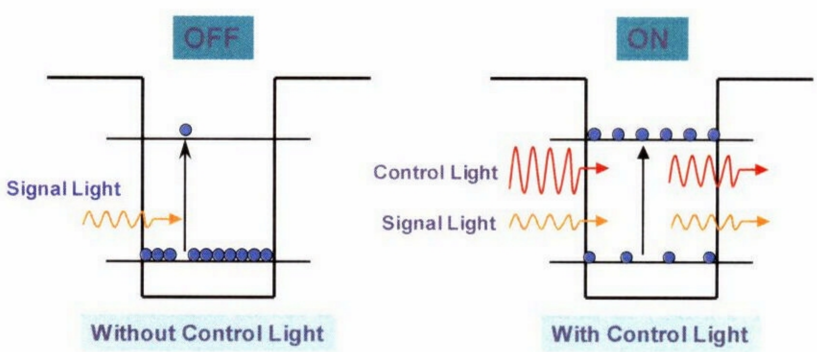

Figure 1.6 Modulation of Intersubband transition by Intersubband transition:
(a) OFF state, (b) ON state

networks, the modulation of intersubband transition by intersubband transition is introduced. Figure 1.6 shows the modulation scheme using the cross absorption modulation technique. Both signal and control pulses are therefore set to be around 1.55 μm with a little bit different in wavelength, while the intensity of the control pulse is much larger than the signal pulse. When only signal pulses are input, all pulses are absorbed due to large intersubband absorption of the quantum wells, and thus no signal light comes out of the devices, which is "off" state. In contrast, when the control pulses are also input, the large control light pulses are absorbed by the quantum wells while exciting most of electrons from the first subband to the second subband, causing the saturation of absorption. Therefore, the signal pulse can pass through the quantum well without being absorbed, which is "on" state. The modulation speed of this scheme is mainly dependent on the carrier relaxation time, which is on the order of sub-picoseconds [71,73]. The ultrafast all-optical switch operating at optical communication wavelength with terabit-per-second class can therefore be realized by this modulation scheme.

1.5 Materials for 1.55-μm Intersubband Transition

The application of ultrafast all-optical switch has led to many attempts to realize intersubband absorption at the wavelength of 1.55 μm. In order to realize such wavelength, the quantum well with large conduction-band offset is required. There are many material systems proposed for this, for example, InGaAs/AlAs, InGaAs/AlAsSb, ZnSe/BeTe, and GaN/Al(Ga)N multiple quantum wells.

1) InGaAs/AlAs MQW

The first material system proposed for 1.55 μm intersubband absorption was InGaAs/AlAs quantum wells. This material system was adapted from GaAs/AlAs quantum wells by incorporating In in GaAs to achieve larger conduction band offset. However, because of large lattice mismatch between InGaAs and AlAs, the growth has to be performed with several techniques such as graded buffer layer and coupled double quantum wells. The intersubband absorption wavelength as short as 1.59 μm was achieved in this material system [77]. This material system, however, could not reach the wavelength of 1.55 μm, while the growth of the high-quality multiple quantum well structure is difficult in this system.

2) InGaAs/AlAsSb MQW

Although 1.59-μm intersubband transition in InGaAs/AlAs quantum wells has been reported, the large lattice mismatch between AlAs and InP substrate either limits the number of quantum wells that can be grown without significant material degradation or any novel growth technique to accommodate the strain. $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ system which is lattice matched to InP is one of the materials for this purpose because of the large conduction band offset of 1.74 eV, much higher than InGaAs/AlAs structure. Moreover, since $In_{0.53}Ga_{0.47}As/AlAs_{0.56}Sb_{0.44}$ system is lattice-matched to InP, it can be grown much easier than InGaAs/AlAs structure. Using this material system, intersubband absorption at 1.30 μm and 1.55 μm was achieved by coupled double quantum wells (C-QW) [80].

3) GaN/AlGaN MQW

Although group III-nitride semiconductor is well known for the applications of blue light-emitting diode (LED) and laser diodes (LD), GaN/AlGaN heterostructure has been also expected for near-infrared intersubband absorption because of its conduction band offset of 2 eV for GaN/AlN MQW. Compared to previously described InGaAs systems, GaN/AlN MQW has larger conduction band offset, and it is interesting to study because of its ultrafast intersubband relaxation [71]. Moreover, since the bandgap for interband transition is at around 360 nm, which is totally different from the intersubband transition wavelength, it is considered that there is no effect of two-photon absorption [60]. However, since there is no lattice-matched substrate, the growth of group III-nitrides has to be performed on lattice-mismatched substrate such as sapphire, making it difficult to grow a high quality MQW layer. The optical communication wavelength of 1.55-μm, with the shortest intersubband absorption wavelength as short as 1.08 μm, has been reported in this material system [88].

4) ZnSe/BeTe MQW

The ZnSe/BeTe system is a novel material system with a type-II band alignment, originally adapted to extend a device lifetime of II/VI blue-green diodes [116]. In this system, a large conduction band offset leads to localizing potentials of 2.3 eV for electrons in ZnSe layers [94]. Moreover, the ZnSe/BeTe system takes the advantage of its higher ionicity in ZnSe layers, regarding the ultrafast carrier relaxation. The ZnSe/BeTe heterostructures can also be grown with high crystalline quality, since both ZnSe and BeTe are lattice matched to GaAs substrate. The intersubband absorption at 1.55 μm with the shortest wavelength has been reported in this material system [95]. The high confinement waveguide can also be achieved in this material system with the use of ZnMgBeSe (E_g = 2.7-4.5), which has low refractive index and is latticed matched to InP, as cladding layer [64].

The material parameters of InGaAs, GaN, ZnSe and CdS relevant to the scattering rate are compared in Table 1.1. The basic rate of GaN is 18 times greater than that of InGaAs, and is the greatest value among any materials. Indeed, the intersubband relaxation time in the GaN QWs is estimated to be 80 fs [67], which is about thirty times shorter than that (2.3 ps) in the InGaAs QW [66]. The experimental results of the intersubband relaxation measurement in GaN/AlGaN MQW were reported at less than 150 fs for the wavelength of 4.5 μm, and at 160 fs for the wavelength of 1.55 μm [71,73]. Considering this ultrafast relaxation, the GaN/AlGaN MQW is one of the most interesting material system for the realization of intersubband ultrafast optical switches.

Table 1.1 Parameters related to LO-phonon scattering rate of each material

	InGaAs	GaN	ZnSe	CdS
E_g (eV)	0.75	3.4	2.8	2.5
m^* (m_0)	0.042	0.2	0.16	0.19
ε_s	14.1	9.5	9.1	10.3
ε_∞	11.6	5.4	5.75	5.2
$\hbar\omega_{LO}$ (meV)	36	88	31	38
W_0 $(p^{-1}s^{-1})$	6.7	121	51	90

1.6 Fabrication of GaN/AlN Multiple Quantum Wells and Nitride-Based Waveguides for Devices

The observation of the intersubband transition is reported mostly in the MQW structure grown by MBE technique. This is because MBE growth technique could give very sharp interfaces with monolayer-level thickness controllability, which is suitable for the design and fabrication of quantum wells for intersubband transition observation. Moreover, MBE benefits from many *in-situ* characterization techniques because of its high-vacuum environment, such as reflection high-energy electron diffraction (RHEED). For $Al_xGa_{1-x}N$/GaN systems, the intersubband transition at 1.55 μm has been firstly reported by Gmachl *et al.* with $Al_{0.85}Ga_{0.15}N$/GaN MQW structure grown on $Al_{0.65}Ga_{0.35}N$ buffer layer [85]. Then shorter intersubband transition with a wavelength range of 1.08-1.61 μm was achieved by Kishino *et al.* using AlN/GaN MQW structure grown on sapphire substrate [88].

On the other hand, the attempt to shorten the intersubband transition wavelength in the MQW structure grown by MOVPE have not attained satisfactory results as the shortest intersubband transition wavelength reported is merely 2.4 μm [83]. One of reasons is that high-Al mole fraction of AlGaN is difficult to be grown by MOVPE because of the large lattice mismatch between AlN and GaN. Nevertheless, MOVPE is advantageous to obtain high crystalline quality for optical emission devices, and it has many advantages for mass production.

The importance of MOVPE growth technique is well known especially in nitride-based semiconductor. Since there is no lattice-matched substrate available, the growth of high-quality buffer layer on lattice mismatched substrate, such as sapphire substrate, is required for the growth of MQW layer. Although the MBE growth technique can grow very high quality MQW, it could not grow high quality buffer layer for the growth of the MQW layer. This made it difficult to realize an intersubband all-optical switch by the MBE. In order to achieve a good quality GaN buffer layer for waveguides, some growth techniques had been applied, such as GaN/AlN superlattice buffer layer, leading to the realization of intersubband ultrafast all-optical switch with distinction ratio of 2 dB [61]. The improvement of the device characteristic was finally achieved by the employment of high-quality GaN buffer layer grown by MOVPE technique. The ultrafast all-optical switch fabricated on such buffer layer with the same structure could give higher distinction ratio of 10 dB with an input switching pulse energy of 150 pJ [62]. The main cause of large switching energy is considered to be the effect of crystalline defects, which induces an extra propagation loss of the waveguide. By the present growth technology, MOVPE growth technique is an indispensable process required for the fabrication of nitride-based ultrafast all-optical switch using intersubband transition. The study of both MOVPE and MBE growth techniques is therefore important for the nitride-based quantum wells.

1.7 Outline of this Dissertation

In this dissertation, the fabrication of GaN/AlN multiple quantum wells and nitride based waveguide structures for the applications of ultrafast all-optical switch utilizing intersubband absorption are described. The details of this dissertation are organized as follows.

In Chapter 2, the epitaxial growths of GaN, Si-doped GaN and GaN/AlN MQW structures for intersubband transition devices are discussed. The GaN buffer layers were grown on the sapphire substrates by metalorganic vapor phase epitaxy and molecular beam epitaxy with the GaN low-temperature buffer layer technique. The optimum growth condition including growth temperature and thickness of GaN low-temperature buffer layer, growth temperature and pressure of the GaN buffer layer are described. The high-quality GaN buffer layer is successfully grown with very high mobility of 537 cm^2/Vs, and carrier concentration of 6×10^{16} cm^{-3}. Furthermore, the doping of GaN with Si up to the carrier concentration of 9×10^{18} cm^{-3} is realized. The growth of high quality MQW structures are achieved by both the metalorganic vapor phase epitaxy and the molecular beam epitaxy. The parameters that affect the quality of the MQW structures are carefully examined. Then, the characterization results of both growth techniques are compared and discussed.

In Chapter 3, the measurements of intersubband absorption in GaN/AlN MQW structure are discussed. Four measurement methods, including Single-pass transmission method, Attenuated total reflection method, Multiple-reflection waveguide method and Waveguide coupling method, are introduced with sample measurement results. Then, the intersubband absorption in GaN/AlN MQW and its interesting characteristics, including wavelength-tunability and effect of built-in electric field, are discussed. The intersubband absorption in MOVPE-grown GaN/AlN MQW is successfully observed at the shortest wavelength of around 2 μm. For the MBE-grown GaN/AlN MQW, it is shown that the near-infrared intersubband absorption wavelength, including 1.55 μm, can be easily achieved. Then, with the measurement results, the problems in achieving near-infrared intersubband absorption wavelength in MOVPE-grown GaN/AlN MQW are discussed.

In Chapter 4, the GaN-based waveguide structure is designed and fabricated. Several waveguide structures with different clad layer materials are proposed. The thicknesses of each layer in the waveguide structures are optimized to achieve the single-mode waveguide with high optical confinement. The fabrication of waveguide is then demonstrated by the inductively coupled plasma etching. The optimization of etching condition is performed to obtain the high-mesa waveguide with smooth sidewall. Finally, the characterization of the as-fabricated waveguide by the waveguide coupling method is demonstrated by making use of the supercontinuum light source. The difference in quality of the waveguide structure grown by metalorganic vapor phase epitaxy and molecular beam epitaxy is then clarified.

In Chapter 5, the AlN-based waveguide structure is proposed as a candidate to fabricate the high-quality waveguide with high optical confinement. Several waveguide structures based on AlN are proposed and designed with careful consideration of the possibility to grow the structure with metalorganic vapor phase epitaxy. Then, the growth of high quality AlN layer is demonstrated by the metalorganic vapor phase epitaxy. Consequently, two types of high-mesa waveguide structure are demonstrated by fabrication with inductively coupled plasma etching technique. Each waveguide structures are then characterized by the Waveguide coupling method using the supercontinuum light source.

In Chapter 6, the fabrication of intersubband transition devices using AlN waveguide structure with GaN/AlN multiple quantum wells is demonstrated for the first time by a combination of two growth techniques: metalorganic vapor phase epitaxy and molecular beam epitaxy. The device can operate in a wavelength range of 1.3-1.55 μm, confirming by the intersubband absorption spectrum measured by the waveguide coupling method using supercontinuum light source. The intersubband absorption saturation of the device is then demonstrated with the pumping of ultrashort optical pulses. The device shows good characteristic of intersubband absorption saturation, with 7 dB absorption saturation observed for input pulse energy of 200 pJ. The operation wavelength tuning of the device is then demonstrated to show the ability to tune the wavelength. Then, the ultrafast all-optical switch operating at 1.55 μm is fabricated using AlN waveguide structure. The switch shows good characteristic with 10 dB absorption saturation for input pulse energy of 90 pJ. Finally, the methods to reduce the switching pulse energy of the device for applications of sub-picosecond ultrafast all-optical switching are discussed.

Chapter 7 summarizes the interesting results and achievements in this dissertation.