CHAPTER 4

FABRICATION AND CHARACTERIZATION OF GAN-BASED WAVEGUIDE STRUCTURES

4.1 GaN-Based Waveguide Design

The growth and characterization of GaN and GaN/AlN multiple quantum wells were described in previous chapter. In order to make the optical devices based on intersubband transition, an optical waveguide must be fabricated. Indeed, designing of waveguide structure is the most important issue, particularly for the devices utilizing the saturation of intersubband absorption. This is because presently such devices still require very high switching pulse energy in order to pump the intersubband absorption in the waveguide to the saturated state [62]. As the amount of absorption in the waveguide is related to the number of quantum wells and optical confinement of the waveguide, the designing of a new waveguide structure which gives good optical-confinement factor is thus thought to be another solution to reduce the switching pulse energy.

In nitride semiconductors, the designing of waveguide structure is even more important and difficult, because the conventional growth technology has some limitations in growing good crystalline quality of compound semiconductors of nitrides. For example, growth of thick AlGaN (or AlN) layers on top of GaN could cause the cracking and dislocations due to large lattice mismatch between AlGaN (or AlN) and GaN, while the growth of AlGaN directly on sapphire could not achieve good crystalline quality by the present growth technology. Therefore, the designing of waveguide structures for nitride based optical devices cannot be performed without consideration of the crystal growth technology. In general, there are two main parameters that require careful consideration in the designing the waveguide structures in this study as follows:

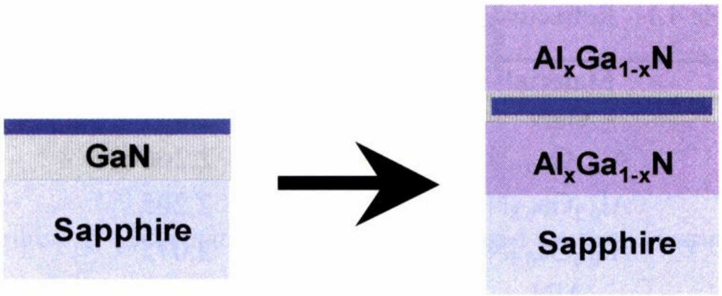
1) Optical confinement in the MQW layer

The optical confinement in the MQW layer should be as high as possible to effectively utilize the intersubband absorption and make it easier to get saturated with lower pumping power.

2) Mode of propagation

The all-optical switch utilizing intersubband absorption is expected to operate at very high speed as fast as 1 Tb/s. To be able to operate with high reliability and stability, the mode of propagation should be single mode.

Essentially it is difficult to find the composition of nitride compound semiconductors that has the lattice constant matched to each others, making it much more difficult to design the waveguide. Three main materials that are widely used and could be grown with high crystalline quality are GaN, AlGaN with a few percents of Al composition, and InGaN with a few percents of In composition. In this study, since the GaN and AlN are used for the MQW layers, the main materials used for designing the waveguide are therefore GaN and AlGaN. For InGaN, since the growth temperature is normally low and much different from that of GaN and AlGaN, it is still not possible to



(a) MQW on GaN (b) Waveguide structure

Figure 4.1 Waveguide structure of nitride-based semiconductor
(a) MQW on GaN, (b) Waveguide structure with cladding layer

fabricate with the conventional growth technique and therefore it is not used in the waveguide designing in this study.

The most original structure which can be easily grown by the MOVPE technique is a MQW layer on top of 1.5-μm-thick GaN layer which is grown on sapphire substrate, as shown in Fig. 4.1 (a). The intersubband absorption measurements of such structure have been already performed in Chapter 3. However, such structure does not give good optical confinement to the MQW layer as there is no cladding layer on top of the structures; the light is thus confined inside the thick GaN layer instead of the MQW layer. To improve the optical confinement, the waveguide structure has to be designed with a combination of a high refractive-index core and low refractive-index cladding layers as schematically shown in Fig. 4.1 (b). With the cladding layers at both sides of MQW layer, the light can be confined into middle of the waveguide structure, increasing the optical confinement factor of the MQW layer.

The designing of optical waveguides in this study has been performed with simulation of different structures using the beam propagation method (BPM) software. The refractive indices of $Al_xGa_{1-x}N$ used in this simulation are calculated from Equation 4.1, which is derived in the literature [168]. Table 4.1 shows the refractive indices of the materials used in this simulation.

$$n\ (1550\ nm) = 0.431\ x^2 - 0.735\ x + 2.335 \qquad (4.1)$$

Table 4.1 Refractive indices of materials used in simulation

Material	Refractive index
GaN	2.335
$Al_{0.1}Ga_{0.9}N$	2.266
$Al_{0.2}Ga_{0.8}N$	2.205
$Al_{0.5}Ga_{0.5}N$	2.075
AlN	2.031

With the MQW core layer set in the middle of the waveguide, two different waveguide structures, which are different in cladding layer, are studied with one-dimensional waveguide simulation of propagation mode in z axis (growth direction), followed by the two-dimensional waveguide simulation to investigate the shape of waveguide geometries as follows:

4.1.1 MQW with GaN cladding layers

GaN is the most fundamental material in the nitride compound semiconductors. The growth of GaN with high crystalline can be easily performed on the sapphire substrate with MOVPE growth technique. Designing of the waveguide structures with GaN cladding layers is therefore interesting to study as we have already known that they are possible to be fabricated by the conventional growth technology.

The waveguide structure that is firstly studied here is the structure composed of MQW layers capped with GaN cladding layers as shown in Fig. 4.2. The thickness of MQW layer is set to be 70 nm, and the average refractive index of 2.06, which is calculated from the estimation of the layer to $Al_{0.5}Ga_{0.5}N$, is used in the simulation. At first, the one-dimensional simulation is used to investigate the mode of propagation and confinement factor in each direction of the waveguide separately. The growth direction of the waveguide (z axis) is especially important to study because it determines the optical confinement of the waveguide core in the vertical direction, and it also determines the possibility that the waveguide structure whether can be grown with high crystalline quality.

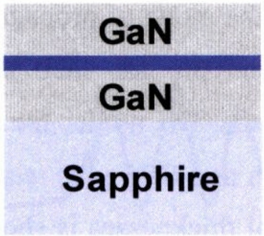


Figure 4.2 Schematic diagram of GaN-based waveguide structure

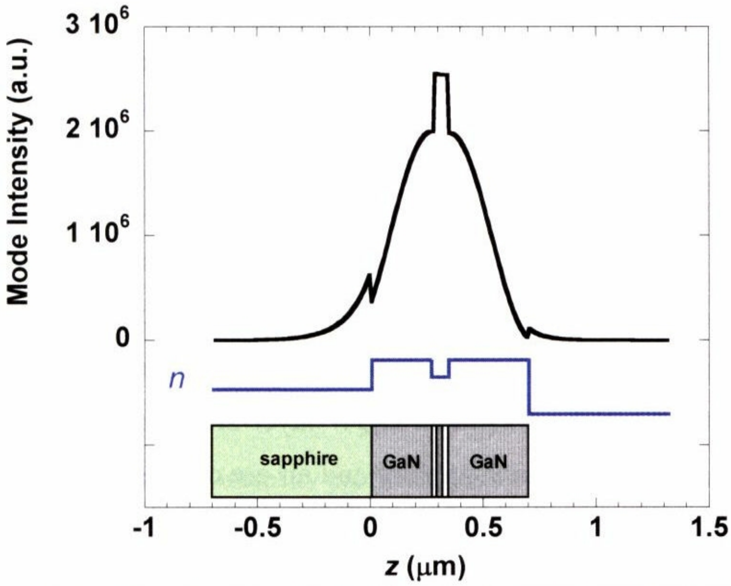


Figure 4.3 TM Mode intensity profile of GaN-based waveguide structure. The thicknesses of bottom GaN, MQW and upper GaN are 0.28 μm, 70 nm and 0.35 μm, respectively.

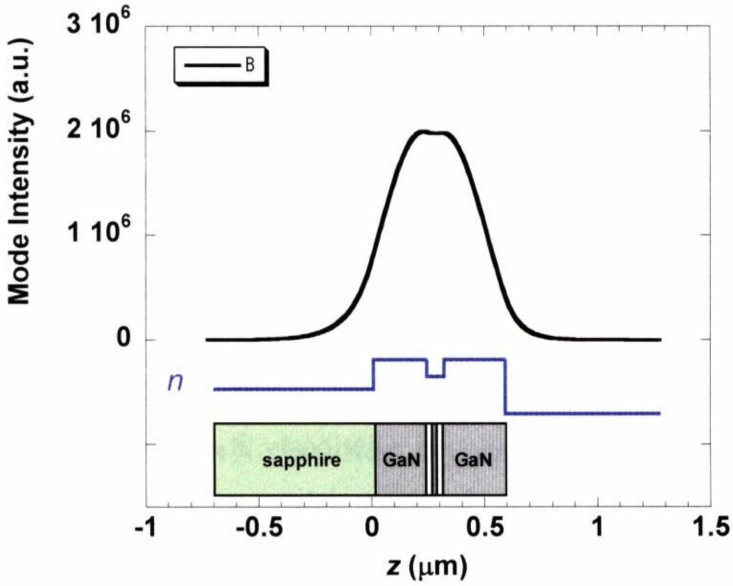


Figure 4.4 TE Mode intensity profile of GaN-based waveguide structure. The thicknesses of bottom GaN, MQW and upper GaN are 0.24 μm, 70 nm and 0.28 μm, respectively.

The critical thickness, where the mode of propagation of the waveguide exists only one mode (single mode), is found out for each layer of the waveguide from the one-dimensional simulation. For the TM mode, the critical thicknesses of lower and upper cladding layers are 0.28 μm and 0.35 μm, respectively. The TM mode intensity profile of the waveguide at critical thicknesses is shown in Fig. 4.3. For the TE mode, the critical thicknesses of each cladding layers are a little bit different: 0.24 μm for lower cladding layer, and 0.28 μm for upper cladding layer. The TE mode intensity profile of the waveguide with these critical thicknesses is also shown in Fig. 4.4.

It can be seen that MQW optical confinement for TM mode propagation is a little bit better than that of TE mode propagation in the optimal structure. The mode intensity profiles of both waveguides show that the optical confinement can be maximized in the MQW layer with the cladding layers. However, some leakage of light at both sides of interfaces, including air/GaN interface and sapphire/GaN interface, are observed in such structures. This is because the structure composes of GaN which has refractive index higher than the MQW layer. The GaN and MQW layer are therefore considered to be parts of the core of waveguides, while sapphire and air are considered to be the cladding parts. The light attenuates very fast in the sapphire and air owing to the large difference of refractive indices between GaN and sapphire, and between GaN and air, respectively. However, this leakage is thought to cause no problem in case that the each interfaces including the waveguide sidewall are nearly perfect. Since the MOVPE growth technique is used to fabricate such structures, the interfaces are considered to be very good, and make this leakage becoming acceptable for the waveguide fabrication.

With such structure, the waveguide could be designed as a single mode waveguide. However, in fact, the growth of GaN requires the minimum thickness of at least 0.8 μm in order to get good crystalline quality enough for the growth of latter structures and fabrication of devices. The structure has to be reconsidered with thicker GaN layers. Therefore the waveguide structure which has the thicknesses of lower and upper cladding layers of 0.8 μm and 0.87 μm, respectively, with the 70-nm-thick MQW layer in the middle of waveguides is investigated. Obviously, it can be seen in the TM mode intensity obtained from the one-dimensional simulation, as shown in Fig. 4.5, that there exist at least 4 modes of propagation, including the fundamental mode, 1st, 2nd and 3rd higher order modes. This kind of multi-mode propagation occurs because the core

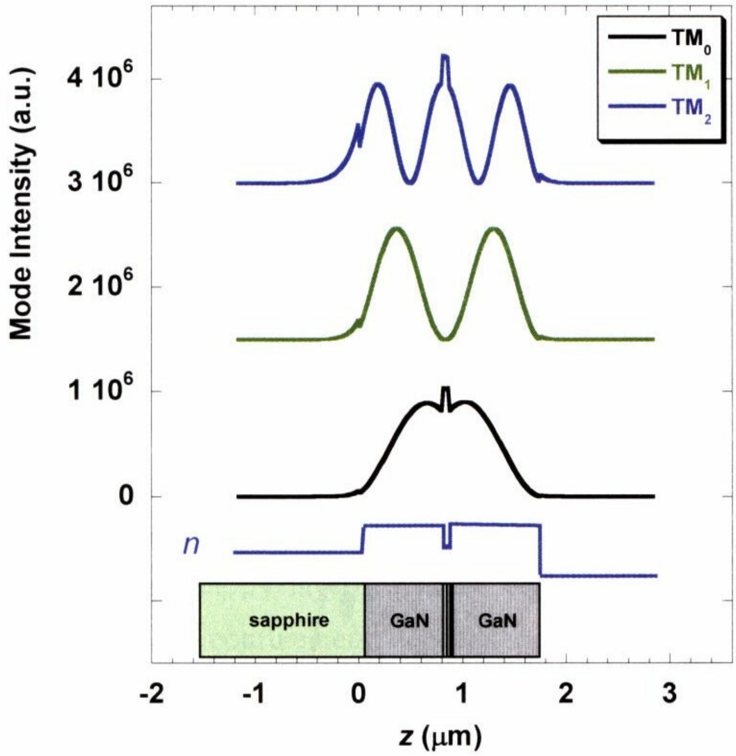


Figure 4.5 TM Mode intensity profile of GaN-based waveguide structure. The thicknesses of bottom GaN, MQW and upper GaN are 0.8 μm, 70 nm and 0.87 μm, respectively.

thickness (the total thickness of lower cladding GaN layer, MQW layer and upper cladding GaN layer) are thicker than the critical thickness obtained from the previous simulation. Although the waveguides show the multi-mode propagation, the higher order modes are normally considered to be difficult to be coupled, especially if the coupling of light from optical fiber to waveguide is well performed for maximum coupling of the fundamental mode. Additionally, in case of characterization of the waveguide, which does not concern with the ultrafast switching experiments, the coupling of light to the higher order mode is considered to cause no problems in the measurements.

4.1.2 MQW with AlGaN cladding layers

In the last section, it has been shown that GaN cannot be a good cladding layer owing to its high refractive index compared to the MQW layer. In order to design a single-mode waveguide, the material with lower refractive index should be used. In this study,

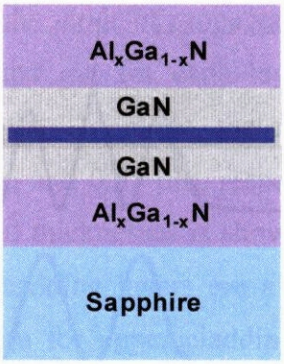


Figure 4.6 GaN-based waveguide structure with AlGaN cladding layers

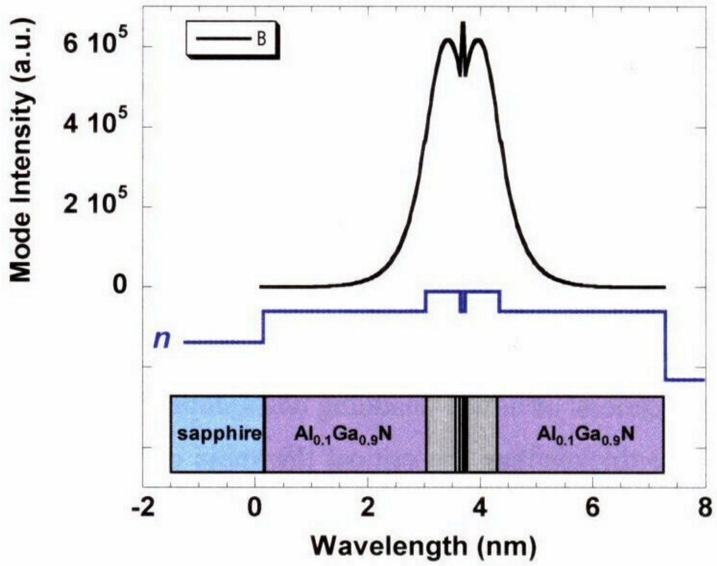


Figure 4.7 TM Mode intensity profile of GaN-based waveguide structure with 3-μm-thick AlGaN cladding layers. The thicknesses of bottom GaN, MQW and upper GaN are 0.65 μm, 70 nm and 0.65 μm, respectively.

AlGaN has been tried to use for cladding layers. AlGaN with a few percent of Al composition could have refractive index lower than GaN, while the lattice constant of AlGaN is relatively close to that of GaN, making it possible to be grown with high quality. However, with only AlGaN cladding layers, the refractive index of cladding layer could be higher than that of MQW layer, GaN is therefore inserted to increase the refractive index of the core part, as schematically shown in Fig. 4.6.

Figure 4.7 shows the TM mode intensity profile obtained from one-dimensional simulation of the MQW with $Al_{0.1}Ga_{0.9}N$ cladding layers. The refractive index of $Al_{0.1}Ga_{0.9}N$ is 2.26, lower than that of GaN (2.35). With this small difference of refractive index, the single-mode waveguide could be obtained. The simulation was performed to find the critical thickness of GaN, while the thickness of $Al_{0.1}Ga_{0.9}N$ cladding layer was fixed at 3 μm. It is found out that the critical thickness of GaN in such structure is 0.65 μm for both lower and upper sides. With GaN thinner than 0.65 μm, only single-mode propagation occurs in the waveguide structure. As can be seen in Fig. 4.7, the mode intensity profile shows that the intensity becomes almost zero in the $Al_{0.1}Ga_{0.9}N$ cladding layer at a distance of 2 μm from the core part. This suggests that the $Al_{0.1}Ga_{0.9}N$ cladding layer could be reduced to be around 2 μm in case that thinner cladding layer is required. Considering the fabrication process, which is described in Section 4.2, thinner $Al_{0.1}Ga_{0.9}N$ layer could be easier to be etched by dry-etching process. The core optical confinement depends on the refractive index difference between AlGaN and core part, including GaN and MQW layer. An increase in Al composition of AlGaN cladding layer therefore gives higher refractive index difference and better optical confinement. However, the growth of high-Al-composition AlGaN cannot be performed easily to obtain high quality. This has been replaced by the use of AlN cladding layer, which is discussed in Chapter 5.

4.1.3 Ridge waveguide and high-mesa waveguide

Before performing the waveguide fabrication, the shape of waveguide should also be studied to design a waveguide with good characteristic. Two types of waveguide geometries including ridge waveguide and high-mesa waveguide are introduced in this section as follows:

1) Ridge Waveguide

The ridge waveguide generally means the waveguide in which etching of the waveguide is performed shallowly, not reaching the core layer of waveguide, as schematically shown in Fig. 4.8 (a). The ridge waveguide is known for low propagation loss since the light is confined in the waveguide but lateral sides of the cores are still connecting to same material of the waveguide. The propagated light is therefore not much interfered by the interface roughness of the sidewall of waveguide. Additionally, the ridge waveguide can get good fiber-to-waveguide coupling efficiency. Moreover, the ridge waveguide is good to suppress the multi-mode propagation in the waveguide because the ridge structure makes the effective refractive index in the horizontal axis becoming no much different at the sidewall of the waveguide. Comparing to the high-mesa waveguide structure, which the refractive index difference is the difference between refractive index of air and waveguide material, the ridge waveguide structure is thus easier to be used for a single-mode waveguide. With these advantages, the ridge waveguide is therefore widely used in fabricating the waveguides.

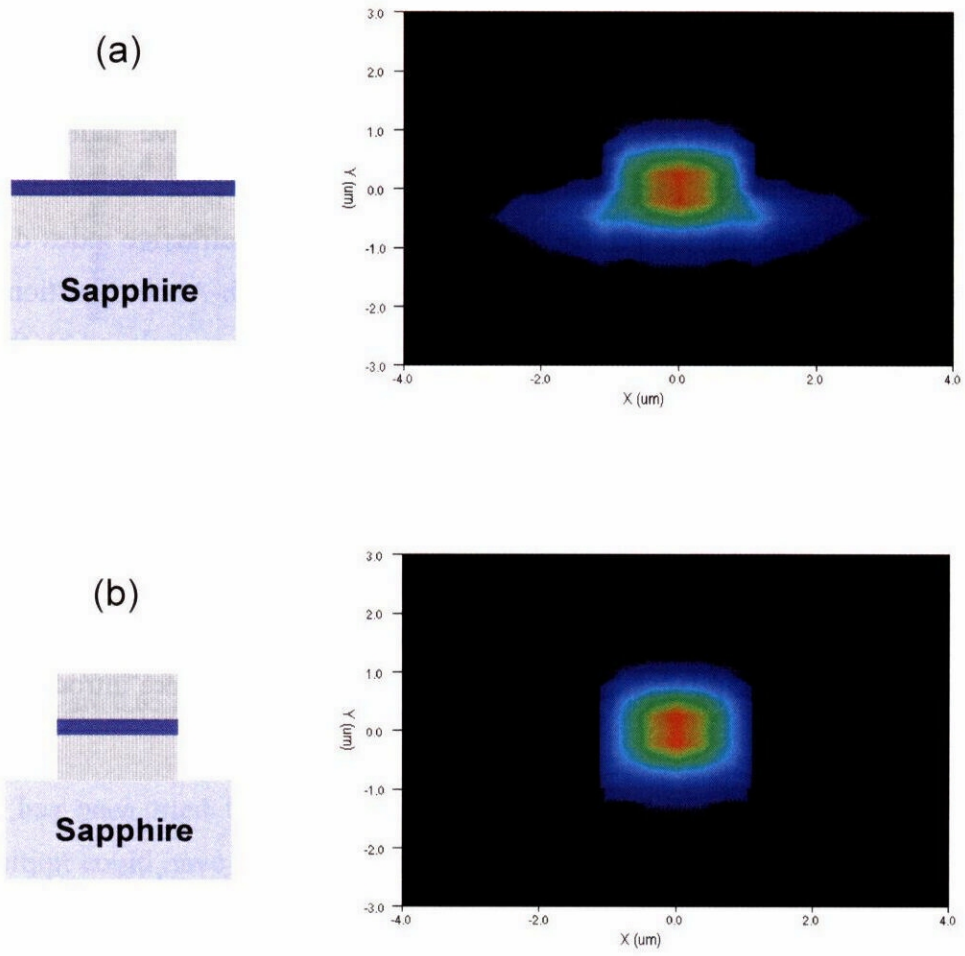


Figure 4.8 Two dimensional TM mode intensity profile
(a) Ridge waveguide (b) High-mesa waveguide

2) High Mesa Waveguide

The high mesa waveguide, in general, means the waveguide which etching is performed deeply until the core part is surrounded by the air, as schematically shown in Fig. 4.8 (b). The high mesa waveguide is well known for the high optical confinement. However, the fabrication is more difficult because the deep etching is needed, while the sidewalls of the waveguide are also required to be smooth. The rough sidewall can cause high propagation loss because the propagated light can be interfered easily at the interface. Moreover, the coupling loss of the fiber to high-mesa waveguide could be high because the coupling of light from the fiber is more difficult. Fortunately, the propagation loss can be reduced by improving the waveguide fabrication process to make waveguide with flat sidewall. The fiber-to-waveguide coupling efficiency can also be improved by performing anti-reflection (AR) coating with optimization of waveguide structure. The high-mesa waveguide is therefore a high-optical-confinement waveguide structure that is highly expected for the realization of intersubband transition devices.

4.2 Fabrication of GaN Waveguide

In this section, the fabrication of nitride-based waveguide is described. Firstly, the fabrication process is explained, followed by the optimization of dry-etching process for the GaN-based waveguide fabrication. Finally, the fabrication of high-mesa waveguide is also demonstrated.

4.2.1 Fabrication process

After growing the MQW with waveguide structure, the waveguide was fabricated as schematically illustrated in Fig. 4.9 by the following procedures:

1) Deposition of SiO_2 for etching mask

To perform etching of GaN and related materials in this research, SiO_2 is used as etching mask. The SiO_2 layer is therefore deposited by magnetron sputtering with a thickness of 0.5-1 μm depending on the required etching depth.