CHAPTER 5

FABRICATION AND CHARACTERIZATION OF ALN-BASED WAVEGUIDE STRUCTURES

5.1 Why AlN?

Fabrication and characterization of GaN-based waveguide has been discussed and found that one of the problems occurred for GaN-based waveguide is that the refractive index of GaN is larger than that of GaN/AlN MQW layer, making it impossible to design a single-mode waveguide with high optical confinement by using GaN cladding layer. The use of AlGaN as cladding layers has shown that the waveguide structure can be designed to be a single-mode waveguide, but the optical confinement factor is rather small. In order to solve this problem, the AlN was proposed to be another candidate for cladding layers of the nitride-based waveguide structures. Using AlN as cladding layers has many advantages for nitride-based waveguide as follows:

1) Single mode waveguide

Refractive index of AlN is as low as 2.06 [168]. This is the lowest refractive-index material in the nitride semiconductors, and it is rather different from refractive index of GaN (2.35), and AlGaN (2.25). AlN can therefore be used as a cladding layer in order to make a single-mode waveguide, where the large refractive index difference can enhance the optical confinement to the core part. Moreover, the refractive index of the core part can be increased with an insertion of high refractive index materials, leading to a waveguide structure with high optical confinement.

2) Low coupling loss

The reflectance of a waveguide facet is a function of the refractive index difference between the air and semiconductor material. Lower refractive index can therefore reduce the reflectance of the waveguide facet. The fiber-to-waveguide coupling loss of AlN waveguide can thus be reduced as it has a lower reflectance than that of GaN.

3) Easy to grow MQW with thick AlN barrier

The GaN/AlN MQW layer can be thought as an AlGaN layer where Al composition is a function of thickness ratio between GaN and AlN. In general, the growth of GaN/AlN MQW for 1.55 μm intersubband absorption requires thin GaN quantum wells with thick AlN barriers. The thick AlN essentially gives high Al composition of the MQW layer, meaning that its lattice constant is close to AlN. Growing the MQW layer with thick AlN barriers is therefore easier for AlN-based waveguide structures than for GaN-based waveguide structures.

4) Good carrier confinement

Leakage of carriers is one of problems that should not occur for the observation of intersubband absorption. However, the tunneling process which is thought to be a cause of the carrier leakage can occur with a rate inversely dependent on barrier height and barrier thickness. High and thick barrier is therefore required to suppress the tunneling process. In the AlN-based waveguide structure, the AlN barriers can be grown thicker than those in the GaN-based waveguide structure, making the tunneling of carriers through barriers being more difficult to occur. Moreover, in the AlN-based waveguide structure, there is no energy level available for leakage because both sides of MQW are surrounded by AlN which has high barrier. The carrier leakage is therefore suppressed in the AlN waveguide. This could improve the characteristic of all-optical switch utilizing intersubband transition. In case of MQW grown on GaN buffer layer, it was reported that the leakage of carriers to an energy level in the GaN buffer layer might have occurred, causing slow recovery time in the switching characteristic [172].

5) Strong built-in electric field

As the lattice mismatch between GaN and AlN is different as large as 2.6 %, the built-in electric field, which is mainly induced by the piezoelectric field effect, is very strong in GaN quantum wells especially when the AlN is used for cladding layers. Indeed, this built-in electric field can help in shortening the intersubband absorption wavelength. Moreover, with a very strong built-in electric field, the intersubband absorption wavelength can be fixed at a wavelength independently to thickness of MQW layer, or number of quantum wells, which is demonstrated in Chapter 6.

5.2 AlN-Based Waveguide Design

In this section, the AlN-based waveguides are designed with the simulation of different waveguide structures using AlN cladding layer. Three types of waveguide are discussed.

5.2.1 AlN clad waveguide

This structure is similar to the MQW with GaN cladding layer, as described in Chapter 4. The structure composes of MQW layer sandwiched by two thick AlN cladding layers as schematically shown in Fig. 5.1. However, this structure is difference from the MQW with GaN cladding layer because the AlN cladding layer has refractive index lower than MQW layer. Considering MQW layer as a core part, the AlN clad waveguide can therefore confine the light inside the core part with single-mode propagation. The TM and TE mode profiles of the waveguide are shown in Fig. 5.2 (a) and Fig. 5.2 (b), respectively. The critical thickness for TM mode was found to be 400 nm for lower cladding layer, and 412 nm for upper cladding layer. With the cladding layer thickness less than the critical thickness, it was confirmed by simulations that the waveguide operates as a single-mode waveguide.

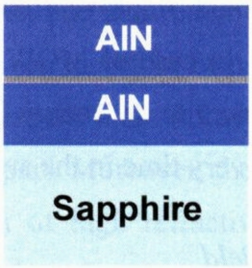

Figure 5.1 Schematic diagram of AlN-based waveguide structure

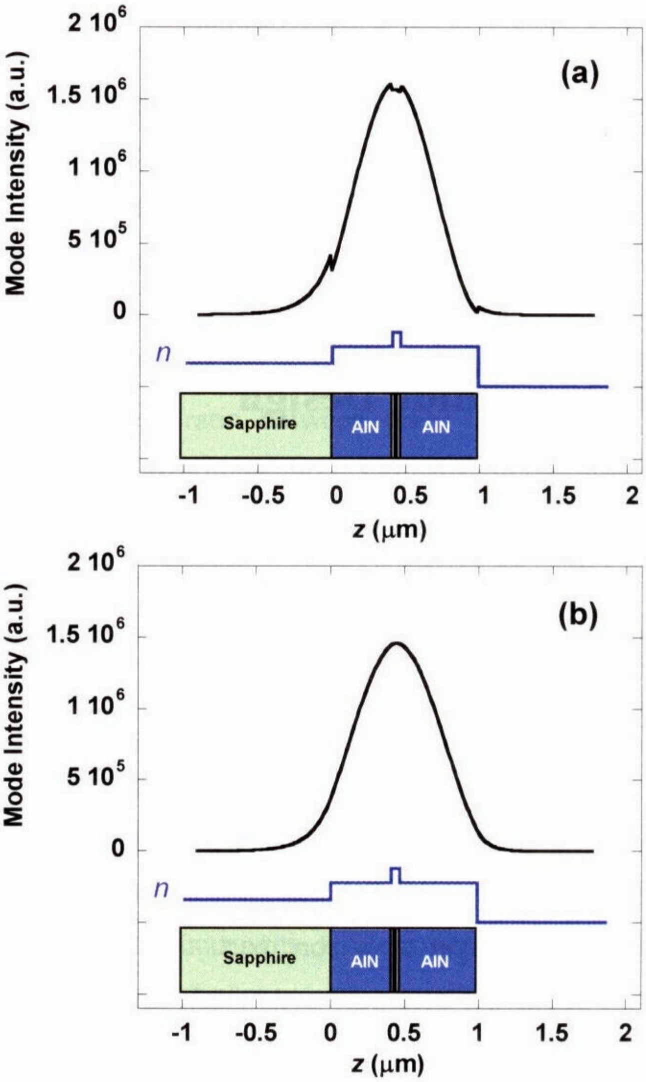

Figure 5.2 Mode intensity of AlN-based waveguide structure. (a) TM mode, (b) TE mode The thicknesses of bottom AlN, MQW and upper AlN are 0.40 μm, 70 nm and 0.41 μm, respectively.

Figure 5.3 shows the simulation results of the optical confinement factor of the MQW core as a function of the MQW thickness. It can be obviously seen in Fig. 5.3 that the optical confinement factor of the MQW core is linearly dependent on the core thickness in such structure. This linear dependence is thought to be a result of small refractive difference between the AlN clad and the MQW core. In order to achieve high optical confinement to the core, the thick MQW is therefore required. Fortunately, using

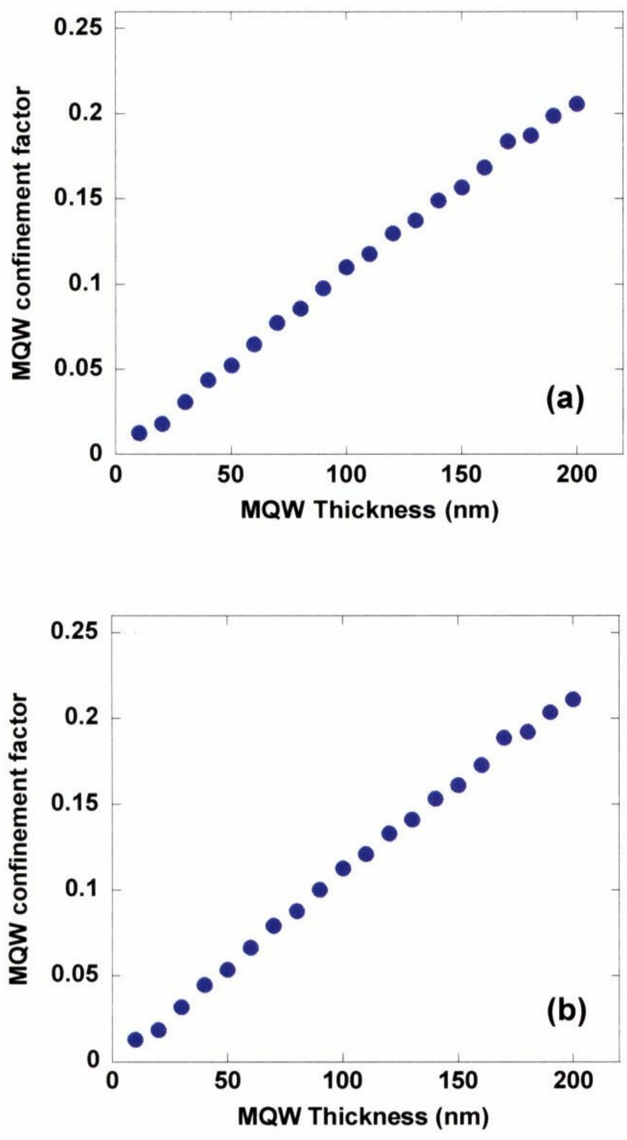

Figure 5.3 Optical confinement factor of AlN-based waveguide structure as a function of MQW thickness. The thicknesses of bottom AlN, MQW and upper AlN are 0.40 μm, 70 nm and 0.41 μm (a) TM mode, (b) TE mode

AlN as cladding layer, the growth of thick MQW is possible by growing thick AlN barriers with thin GaN quantum wells, making the Al composition of MQW layer close to that of AlN cladding layer. In general, GaN quantum wells with thickness less than their critical thickness on AlN are required for achieving near-infrared intersubband absorption wavelength, while thick AlN barriers are preferable for achieving good-characteristic intersubband absorption. This designed structure is therefore expected for the fabrication of the high quality waveguides for intersubband absorption devices.

5.2.2 AlN clad waveguide with GaN guiding layer

The structure with AlN cladding layer can be used as a single-mode waveguide as described in the last section, but the optical confinement is quite low in such structure owing to small refractive index difference between the MQW layer and AlN cladding layers. To improve the refractive index difference, some layers with high refractive index should be inserted between the MQW layer and AlN cladding layer, for example, inserting GaN as schematically illustrated in Fig. 5.4. In this case, the core part can be determined as summation of MQW layer and the GaN layer. Since GaN has refractive index higher than the MQW layer, the effective refractive index of the core part can be improved with insertion of GaN as guiding layers. Figure 5.5 shows the simulated TM and TE mode intensity profiles of AlN waveguide with GaN guiding layers. The thickness of AlN cladding layers and GaN guiding layers were 1 μm and 200 nm,

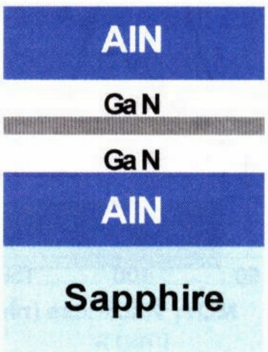

Figure 5.4 Schematic diagram of AlN-based waveguide structure with GaN guiding layers

respectively. It can be seen in the figure that this waveguide structure provides very good TM and TE mode intensity profiles; the profile is symmetrical for both upper clad and lower clad. Both the TM and TE mode intensity in the MQW layer increases obviously with the insertion of GaN guiding layers. Moreover, the light is confined mainly in only core part (MQW and GaN guiding layer) as a result of the improved optical confinement of the core. This kind of intensity profile is thought to be able to easily couple with the light from optical fiber. The thickness of the AlN cladding layer can be increased as thick as desired, while the optical confinement of the core can be increased by optimizing the thickness of the GaN guiding layer.

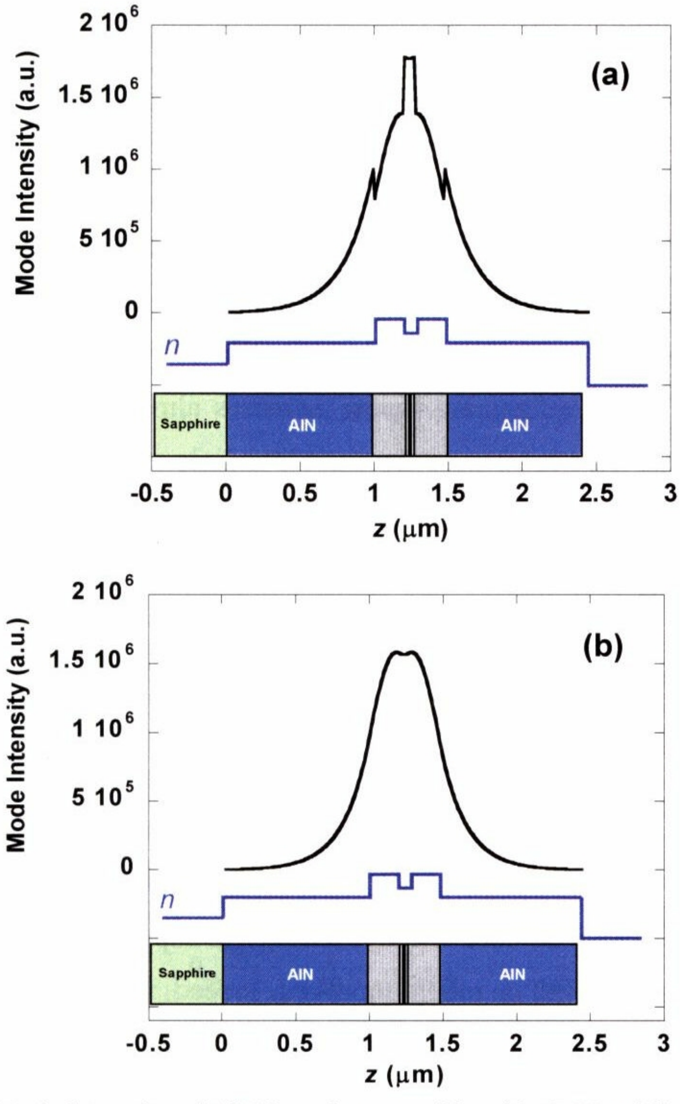

Figure 5.5 Mode intensity of AlN-based waveguide with GaN guiding layers: (a) TM mode, (b) TE mode The thicknesses of AlN cladding layers and GaN guiding layers are 1 μm and 0.2 μm, respectively. MQW thickness is 70 nm.

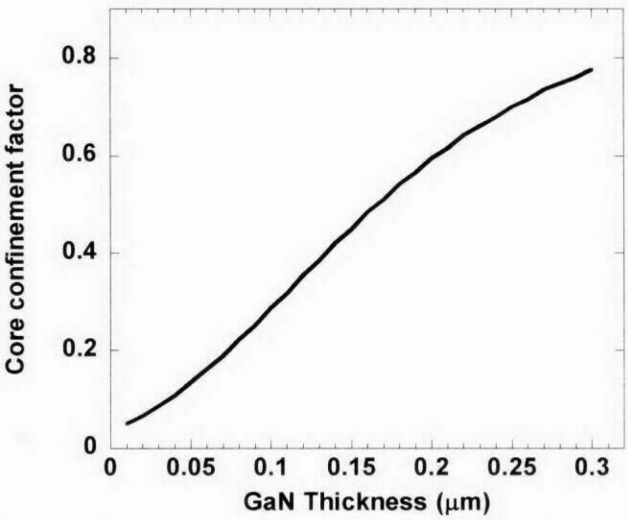

Figure 5.6 Core optical confinement factor of AlN-based waveguide with GaN guiding layer as a function of GaN thickness. The thicknesses of AlN cladding layers and GaN guiding layers are 1 μm and 0.2 μm, respectively. MQW thickness is 70 nm.

In order to compare this result to the previous waveguide structure, the TM-mode optical confinement factor of the core (MQW and GaN guiding layer) as a function of the GaN layer thickness is calculated as shown in Fig 5.6. It can be obviously seen that the optical confinement factor of the core drastically increases compared to the previous waveguide structure. The confinement factor increases almost linearly with the GaN guiding layer thickness. This is because the light is mainly confined in the core, where the effective refractive index of the core increases with the GaN thickness.

The optical confinement factor is also calculated for the MQW layer only, as shown in Fig. 5.7. It can be seen that the optical confinement factor of the MQW is almost linearly dependent on the GaN layer thickness, similar to that of the waveguide core. Comparing these results with those in Fig. 5.3, the optical confinement factor of the waveguide with GaN cladding layers increased, showing the improvement of optical confinement with the insertion of GaN guiding layers. It should be noted here that the increase of optical confinement in the MQW layer is not much, but because the light can be confined into the waveguide core without leakage to sapphire substrate and air, the waveguide characteristic should be much improved. Indeed, for the previous waveguide structure without GaN guiding layer (Fig. 5.1), the whole waveguide (lower AlN clad, MQW and upper AlN clad) works as a waveguide core while using the air and sapphire as clad. With the insertion of GaN guiding layers, the waveguide core is limited to be only GaN guiding layer and MQW, leaving AlN cladding layer working as clad. This structure provides the ability to design the waveguide core independently without consideration of the AlN-clad thickness. It is therefore a very interesting structure that should be investigated in order to improve the waveguide characteristic for low switching-energy all-optical switch utilizing intersubband transition.

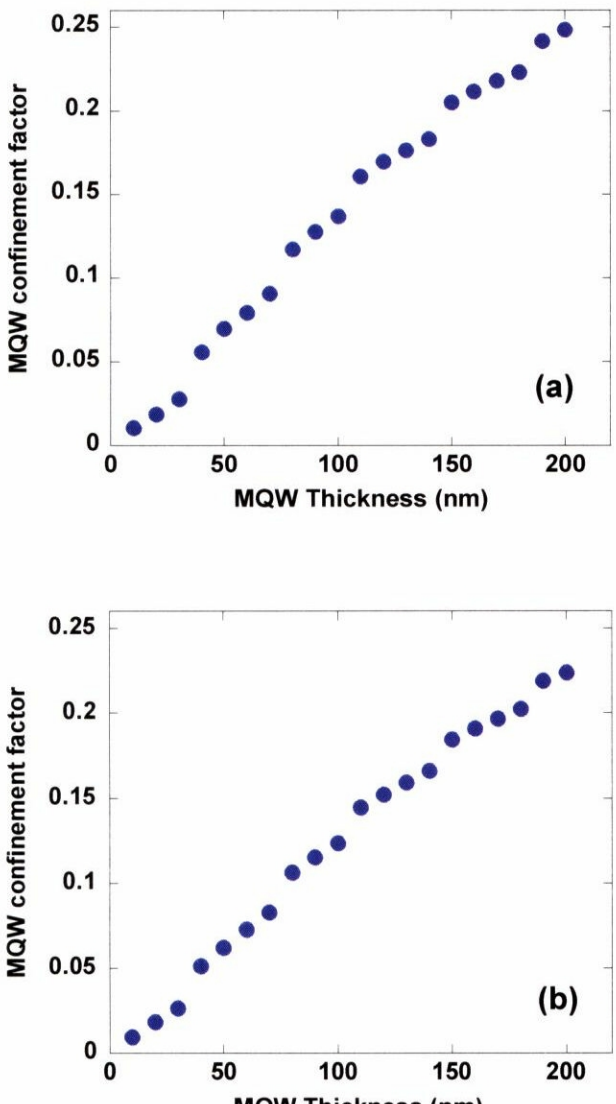

Figure 5.7 MQW optical confinement factor of AlN-based waveguide with GaN guiding layer as a function of GaN thickness. The thicknesses of AlN cladding layers and GaN guiding layers are 1 μm and 0.2 μm, respectively. MQW thickness is 70 nm.

5.2.3 AlN clad waveguide without upper AlN cladding layer

Even though improvement of optical waveguide has been demonstrated by simulation with the insertion of GaN guiding layer, the growth of such structure is considered to be quite difficult owing to the large lattice mismatch between GaN and AlN. The growth of GaN guiding layer on AlN clad layer thus requires some special growth technique to reduce the stress occurred from such lattice mismatch. Another way to solve this problem is to use $Al_{0.5}Ga_{0.5}N$ as guiding layers instead of GaN. This way could reduce the optical-confinement ability of the core part, but the waveguide structure could become easier to grow by the conventional growth techniques.

Another problem in the growth of such structures is the difference growth temperature of AlN and GaN. Since the growth of upper AlN cladding layer must be performed at high temperature, it is very difficult to grow because the growth of such cladding layer must be done after the growth of GaN/AlN MQW and GaN layers. Too high temperature during growth of AlN cladding layers could destroy the crystalline quality of previously grown GaN/AlN MQW and GaN layer. Another waveguide structure without upper AlN cladding layers has therefore been proposed as schematically shown in Fig. 5.8. Obviously it can be seen that this structure has no big different with the previous structure, but the upper cladding layer is not required, while the core thickness is optimized to get the high optical confinement. Figure 5.9 shows the TM mode intensity profiles of the optimized GaN guiding structures on 1-μm-thick AlN cladding layer without upper AlN cladding layer. The optimal thicknesses of bottom GaN guiding layer, MQW layer, and upper GaN guiding layer of such structure were found to be 380 nm, 70 nm, and 540 nm, respectively. The TM mode intensity profiles in Fig. 5.9 show high intensity in the MQW layer, indicating the good optical confinement of core part. The optical confinement factor of the MQW layer as a function of the MQW thickness could be calculated as shown in Fig. 5.10. Comparing the result of Fig. 5.10 with Fig. 5.7, the confinement factor dependence shows very similar relation to the structures with upper cladding layer, although a little bit decrease in optical confinement factor can be observed. The structure without upper cladding layer is considered to be much easier to fabricate than the structure with cladding layer; therefore the structure without upper cladding layer is expected as another candidate for the high-confinement waveguide of nitride-based semiconductors.

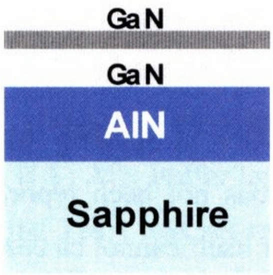

Figure 5.8 Schematic diagram of AlN-based waveguide structure without upper AlN cladding layer

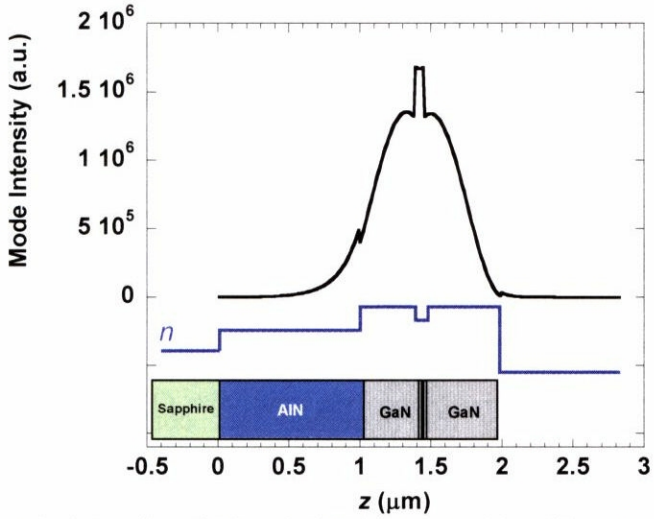

Figure 5.9 TM mode intensity of AlN-clad GaN waveguide without upper AlN cladding layer as a function of GaN thickness. The thicknesses of AlN cladding layers and GaN guiding layers are 1 μm and 0.2 μm, respectively. MQW thickness is 70 nm.

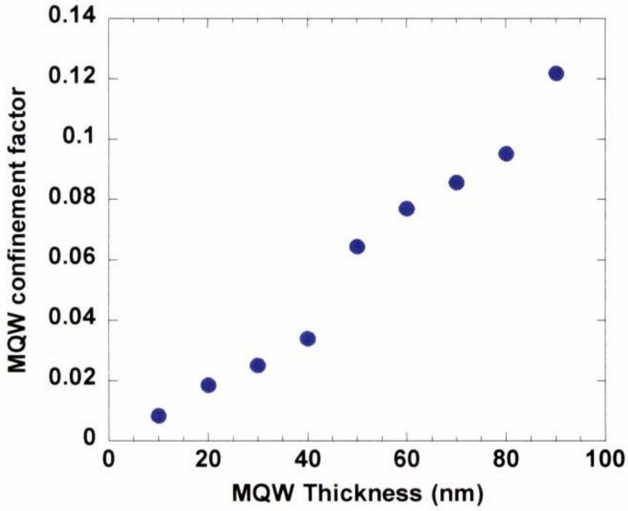

Figure 5.10 MQW optical confinement factor of AlN-clad GaN waveguide without upper AlN cladding layer as a function of GaN thickness. The thicknesses of AlN cladding layers and GaN guiding layers are 1 μm and 0.2 μm, respectively. MQW thickness is 70 nm.