CHAPTER 3

MEASUREMENTS OF INTERSUBBAND ABSORPTION IN GaN/AlN MULTIPLE QUANTUM WELLS

3.1 Measurements of Intersubband Absorption

The intersubband absorption is typically valid for the light that has electric-field components in the direction perpendicular to the quantum well. This makes the intersubband absorption normally polarization dependent; only TM polarization light is absorbed while TE polarization light is transition-prohibited. This is called selection rule. It was shown in the literature that this selection rule is always true in the GaAs-based quantum wells [146]. The measurements of absorption for TM polarization are much more difficult than for TE polarization. This is because the light beam from light source in a measurement system must be coupled in a direction that is parallel to the quantum wells, which is normally thin on the order of nanometers. The diameter of the light beam in conventional infrared measurement system, such as Fourier transform infrared (FTIR) spectrometer, is usually small on the order of millimeters, resulting in very low efficiency of light coupling into the MQW, especially for TM polarization. Coupling of the TM polarization light to a specimen is therefore an important issue for the measurements of intersubband absorption. In this study, the intersubband absorption measurements are performed with 4 methods, including Single-pass transmission, Attenuated total reflection, Multiple reflection, and Waveguide coupling.

3.1.1 Fourier transform infrared spectrometer

Before beginning to discuss on the intersubband absorption measurements, in this section, the Fourier transform infrared spectrometer (FTIR) is introduced. The FTIR spectrometer is typically based on a Michelson interferometer as shown in Fig. 3.1. In FTIR spectrometer, light from an infrared light source is collimated and incident on a beam splitter. An ideal beam splitter creates two separate optical paths by reflecting 50% of the incident light and transmitting the remaining 50%. In one path the beam is reflected by a fixed-position mirror back to the beam splitter where it is partially reflected to the source and partially transmitted to the detector. In the other arm of the interferometer, the beam is reflected by the movable mirror that is translated back and

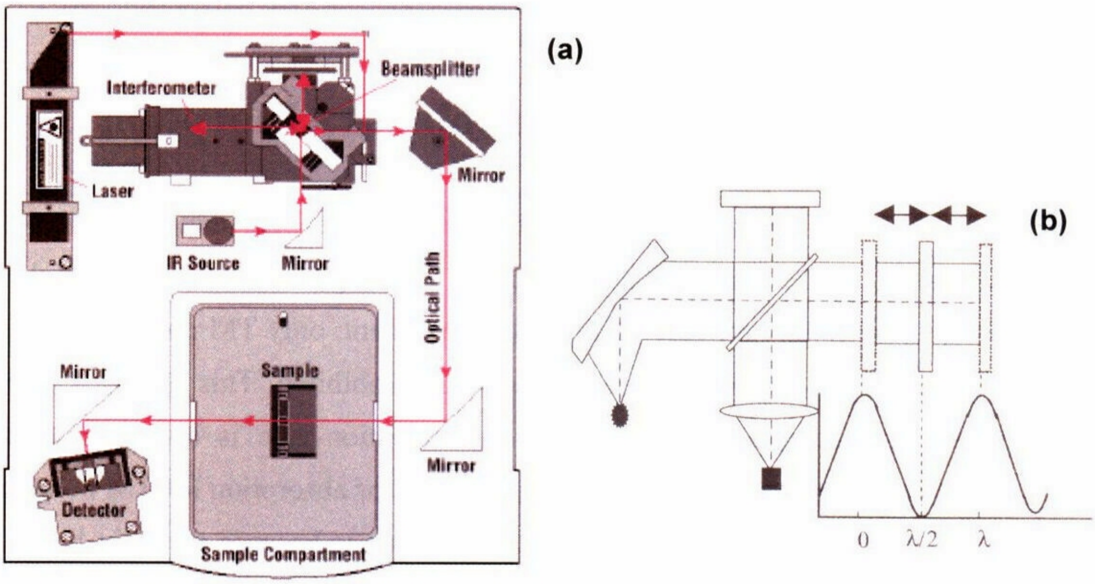

Figure 3.1 Fourier transform infrared spectrometer
(a) Schematic diagram of devices in spectrometer,
(b) Optical interferometer with moving mirror

forth and maintained parallel to itself. The interference of two beams of light waves propagated through two separate optical path lengths is thus produced when they are combined. For different positions of the movable mirror the two partial waves obtain different phase shift with respect to each other. Therefore, on the detector, the radiation field is superimposed with a time-delayed copy of itself. Hence, what is basically measured when the detector signal is recorded while the mirror moves is the autocorrelation function of the radiation field, which is called the interferogram in the FTIR spectroscopy. The Fourier transform of this autocorrelation function is the desired power spectrum in a frequency domain.

In the FTIR spectrometer, there are three important components that determine the wavelength range of the measurement, which are light source, beam splitter, and detector. In this study, there are 2 sets of these components which can be set up for a wide range of measurements from mid-infrared to near-infrared region. The liquid-nitrogen cooled MCT-detector is used in all measurements. This detector can detect the light in very wide range from near-infrared to far-infrared (450 – 11000 cm^{-1}). For the mid-infrared region, a mid-infrared light source and KBr Beam-slitter are used. This combination enables the measurement in the wavelength range from 450 – 4500 cm^{-1}. For the measurement in the near-infrared region, the Tungsten halogen lamp is used with the Quartz Beam-slitter, which enables the measurement range from 3500 – 11000 cm^{-1}.

3.1.2 Single-pass transmission method

This single-pass transmission method is the simplest way to perform intersubband absorption measurements. The light is coupled to a sample with an incident angle to wafer surface at Brewster angle, as schematically illustrated in Fig. 3.2. At the Brewster angle, reflection of p-polarization light reduces to minimum, resulting in clear transmission spectra without noise generated by optical interference. The p-polarization contains two components of light: one with electric field perpendicular to the MQW (TM-polarization) and one with electric field parallel to the MQW (TE-polarization). Only the light with electric field perpendicular to quantum well can be absorbed with intersubband transition. The amount of light coupled to the direction of absorption therefore depends on the angle of incidence, which is fixed to the Brewster's angle in

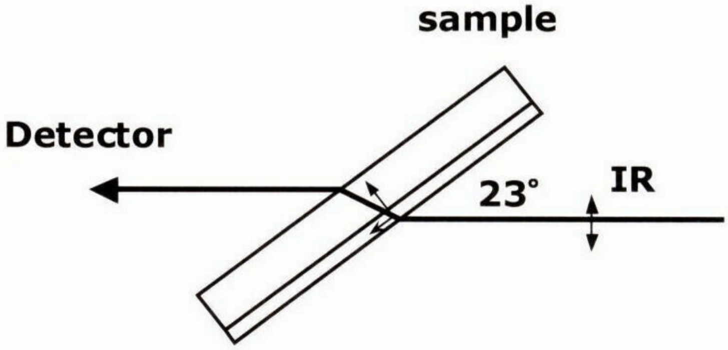

Figure 3.2 Schematic diagram of intersubband absorption measurement by Single-pass transmission method

this experiment for maximum coupling. One can see that light coupled to the quantum well in TM polarization is only a part of p-polarization light. This makes it difficult to observe the intersubband absorption by the single-pass transmission method.

Figure 3.3 (a) and 3.3 (b) shows the transmission spectra measured by the single pass transmission method for the various well thicknesses of GaN/$Al_{0.6}Ga_{0.4}N$ MQW and GaN/AlN MQWs, respectively. The angle of incidence was adjusted to the Brewster angle of the substrate, which was calculated to be around 23°. As can be seen in the figures, absorption dips can be observed in the single-pass transmission spectra. The absorption dips are, however, very weak in the order of a few percents of transmitted

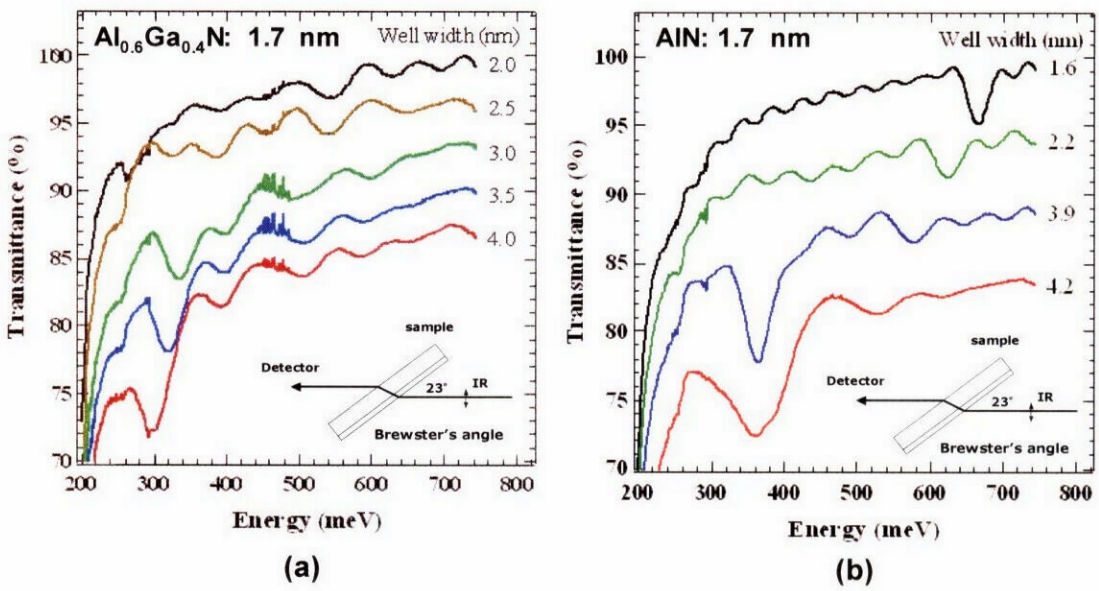

Figure 3.3 Transmission spectra measured by Single-pass transmission method for p-polarization (a) GaN/$Al_{0.6}Ga_{0.4}N$ MQW, (b) GaN/AlN MQW

light. This absorption could become very difficult to be seen for thin quantum wells, as the volume of doping region decreases, causing too small amount of active carriers in the wells. One can also see that besides the absorption dips, optical interference waves also show up in the transmission spectra, as a result of the reflection of light between the air/MQW and air/sapphire interface. This could make it even more difficult to detect the absorption dip for the quantum wells that has weak absorption. With only single pass of transmission, the absorption must be strong otherwise the absorption will be hidden by the optical interference waves. In case that absorption is not strong enough, the intersubband absorption can be strengthened by increasing carrier concentration by doping during the growth process. In order to detect the absorption by this method, the carrier concentration at least 1×10^{19} cm^{-3} in the quantum wells is necessary.

3.1.3 Attenuated total reflection method

Attenuated total reflection (ATR) is another technique that is applied for the observation of intersubband absorption. In ATR technique, a high refractive-index material, such as Silicon (Si) and Germanium (Ge), is used for waveguide geometry, as illustrated in Fig. 3.4. The light is incident and coupled at one side of the ATR prism, making the light propagating inside the waveguide geometry. The intersubband absorption in a semiconductor wafer can be measured by attaching the wafer to the ATR prism with a close contact, and then performing the transmission spectra measurements by FTIR spectrometer. Essentially, the light propagates inside the crystal while making total reflection at the interface of ATR-prism and air, and the interface of ATR-prism and

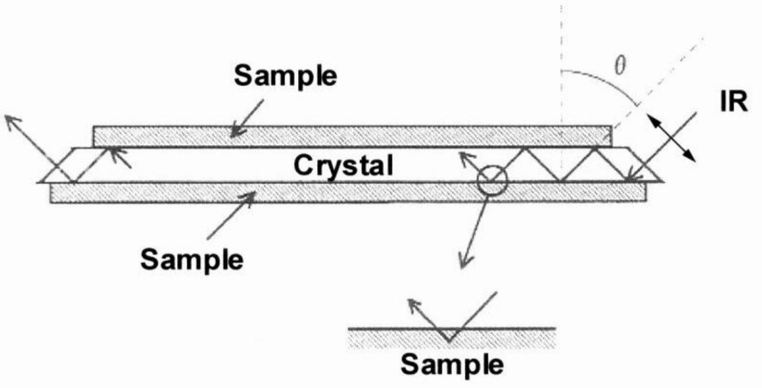

Figure 3.4 Schematic diagram of intersubband absorption measurement by attenuated total reflection method

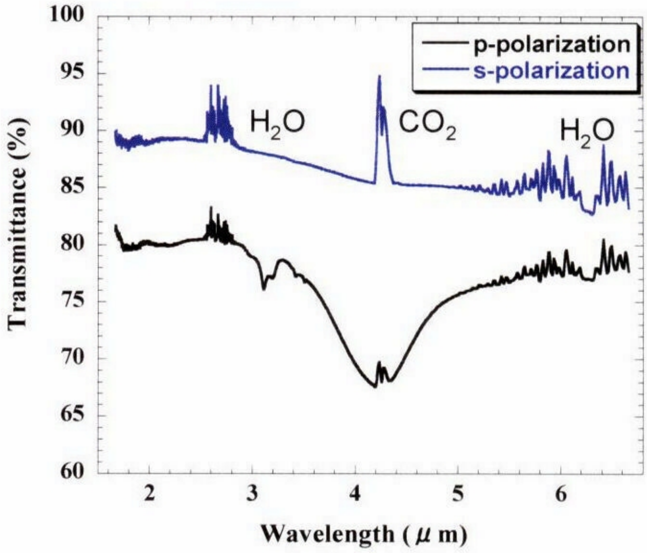

Figure 3.5 Transmission spectra measured by attenuated total reflection method

wafer. In the same time, some part of light, namely evanescence light, also penetrate to the wafer with a depth, usually a few hundred nanometers, depending on the refractive index difference between ATR prism and the wafer. The absorption can thus be measured only if the absorption exists within a-few-hundred-nanometer depth from the wafer surface. The penetration depth can be calculated by:

$$d = \frac{\lambda}{2\pi\left(\sin^2\theta - n_{21}{}^2\right)^{1/2}} \tag{3.1}$$

where λ is the wavelength of incident light, $n_{21} = n_2/n_1$, n_1 and n_2 are the refractive indices of the ATR prism and the wafer, respectively. θ is the angle of incident.

Figure 3.5 shows the transmission spectra of both s-polarized and p-polarized light taken with ATR method for a 100-period $GaN/Al_{0.6}Ga_{0.4}N$ MQW structure. The GaN well and $Al_{0.6}Ga_{0.4}N$ barrier thicknesses were 4.0 nm and 1.7 nm, respectively. As seen in the figure, clear transmission spectra for both s-polarized light and p-polarized light can be measured without interference waves. This is because there is no light path that can cause the interference inside the ATR-crystal. One can thus clearly see that there is strong absorption as large as 25% for p-polarized light, while there is no absorption observed for the s-polarized light. This confirms the existence of intersubband absorption in the fabricated MQW structure. It can be seen that the intersubband absorption measurements by ATR method can increase the sensitivity of measurements. However, the penetration depth is a wavelength-dependent parameter, as can be seen in Eq. 3.1. The penetration depth decreases with shorter wavelength, becoming less than 100 nm for a wavelength of 1.5 μm. Therefore, the measurement of intersubband absorption in near-infrared wavelength range is difficult to be performed by the ATR method, unless the MQW is doped with high carrier concentration.

3.1.4 Multiple reflection method

This method is the most popular one for the intersubband absorption measurements since it has high responsivity to detect the intersubband absorption. It is widely used for the intersubband absorption measurements of many kinds of materials, such as GaAs-based quantum wells [147]. In this method, the idea of total reflection as similar as ATR method has been applied, but the light path is changed from the ATR-prism to the wafer that is fabricated as waveguide geometry, as illustrated in inset of Fig. 3.6. In order to perform this measurement, however, the samples have to be fabricated to be a waveguide geometry which has two ends polished at 45° for a good coupling efficiency. In this study, the polishing process was performed by a polishing machine with a

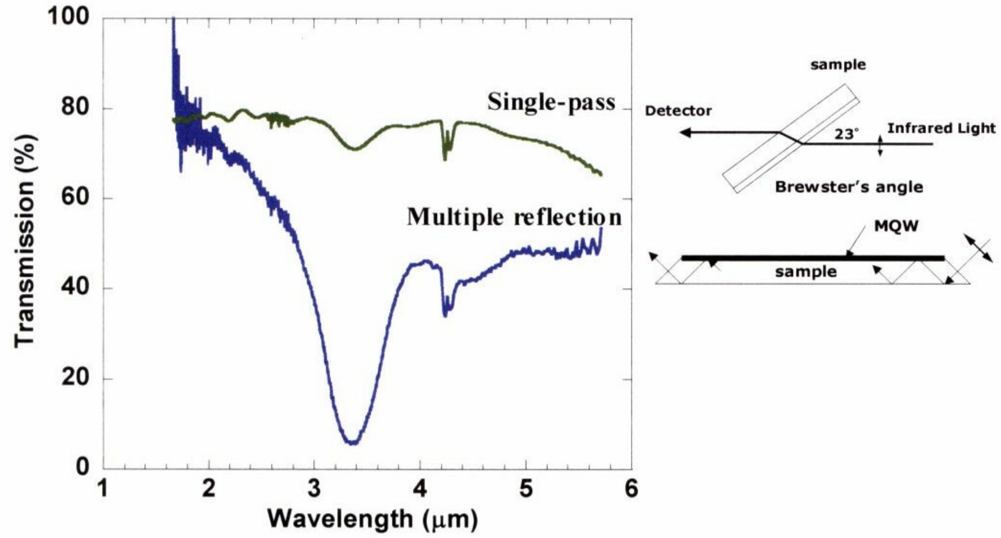

Figure 3.6 Transmission spectra measured by Multiple-reflection method compared with Single-pass transmission method
Inset: schematic diagram of both measurement methods

handmade 45° polishing holder, using electronic wax to attach the samples to the polishing holder.

Figure 3.6 shows the transmission spectra of p-polarized light measured by both the single-pass transmission method and the multiple reflection method for a 200-period GaN/AlN MQW sample, which has GaN well and AlN barrier thickness of 3.9 nm and 1.5 nm, respectively. As seen in the figure, the absorption can be observed with both measurement methods, but it can be much obviously seen by the multiple-reflection method. For MQW samples with a number of quantum well of less than 100 periods, it is very difficult to detect the absorption by single-pass transmission method, but it is still detectable by Multiple-reflection method. As this method can detect even a weak absorption much better than the single-pass transmission method, it is mainly used for measurements in most of experiments in this study.

3.1.5 Waveguide coupling method

The waveguide coupling method is the only way that can effectively couple the light to the TM polarization, the polarization that electric field is perpendicular to quantum wells, without component of TE polarization. This method utilizes the waveguide structure, therefore requiring the waveguide fabrication and waveguide measurement system. After fabricating the waveguide, the light from optical fiber can be coupled to the waveguide using a taper fiber, then propagating in the waveguide with the unchanged polarization. If the polarization of input light is adjusted to the TM mode, the absorption will be so strong that even the weak absorption that is invisible for multiple-reflection method can be detected easily. This is because a laser is used as a light source, and by using a polarization controller, the polarization of the light can be controlled to be TM polarization without leakage to TE polarization.

In this study, this measurement method was demonstrated for the first time thanks to the development of supercontinuum light source [148-155]. The experimental set up for waveguide coupling method requires coupling of the light to waveguide. Therefore, the fabrication of optical waveguide is necessary for this measurement method. The details of this measurement method are therefore included with the fabrication of waveguide, and are described in Chapter 4.