Near-infrared optical absorption in GaN/AlN quantum wells grown by molecular-beam epitaxy

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Abstract. Optical absorption of s- and p- polarized light was studied in GaN/AlN quantum wells in the near-infrared spectral range. An absorption peak associated with intersubband electron transitions in quantum wells was observed near a wavelength of 1.55 µm. Optoelectronic devices based on these structures can be used in fiber-optic telecommunication technologies.

1. Introduction

At present, intersubband optical transitions in III-V-based quantum well (QW) structures, such as GaAs/AlGaAs, InGaAs/AlInAs, GaInAs/AlAsSb, etc., are used in IR optoelectronics operating in the mid-IR (3-8µm) and THz spectral ranges. The development of shorter-wavelength unipolar QW devices (< 3µm) using these structures is difficult due to their insufficient conduction band offset and poor optical transparency [1]. One of the possible solutions is to use intersubband electron transitions in QW structures based on wide bandgap III-Nitride semiconductors (GaN, AlN, InN and their alloys) with a high conduction band offset (~1.8 eV for GaN/AlN) and excellent transparency [2]. These QW structures can be designed so that the energy of electron transitions between the first and second quantum-size levels corresponds to the transparency window of the optic fibers at 1.55 µm. The feasibility of the GaN-based intersubband technology in the telecommunication spectral range was predicted early by Suzuki et al. [3,4]. They proposed to use GaN/AlN QWs to fabricate fully optical switches with a data transfer speed of the order of Tb/s due to the ultrafast intersubband relaxation time (in the range of 140-300 fs) in the QWs associated with the strong interaction of electrons with longitudinal optical phonons.

This paper reports on the observation of the intersubband optical absorption in a GaN/AlN QW structure specially designed for further manufacturing high-frequency optical switches, optical modulators, and IR photod Detectors.

2. Methods

The 25-period GaN/AlN multiple QW (MQW) structure was grown by plasma-assisted molecular beam epitaxy on a c-Al₂O₃ substrate atop of a 2 µm thick AlN buffer layer, as described in detail elsewhere [5]. To adjust the wavelength of the intersubband transition to 1.55 µm, the QW thickness was chosen equal to 1.8 nm. The 5 nm-thick AlN barriers were doped with Si donors with a concentration of 5·10¹⁸ cm⁻³.

It is well known that the normal incidence geometry of the experiment is not suitable for the intersubband absorption investigation due to selection rules. To study the intersubband light absorption...
for two light polarizations, we used a multipass sample geometry where two opposite sample facets were ground at an angle of 45°, which allowed the incident radiation to pass 8 times through the QW structure.

The intersubband light absorption spectra were measured using a Bruker Vertex 80v vacuum Fourier transform spectrometer. A standard globar built into the spectrometer was used as a broadband IR radiation source. The light intensity transmitted through the sample was measured by a pyroelectric photodetector.

3. Results and discussion
The transmission spectra of $p$- and $s$-polarized light were measured at room temperature (see figure 1). For $s$-polarized light, the interference was detected associated with light reflection between the inner structure layers. The distance between the interference peaks $\Delta \delta$ corresponds to the width $d$ of the AlN buffer layer

$$d = \frac{1}{2n\Delta \delta \cos \theta},$$

(1)

where $n$ is the refractive index, $\theta$ is the incidence angle. Thus, it can be assumed that interference takes place as a result of reflecting between the AlN/Al$_2$O$_3$ interface and the structure surface.

![Figure 1](image)

**Figure. 1.** Intensity spectra of light transmitted through the 1.8 nm-GaN/5 nm-AlN MQW structure at room temperature for two light polarizations.

To explain the presence of interference for $s$-polarized light and its absence for $p$-polarized light, we calculated the dependence of the reflection coefficient $R$ on the incidence angle at the AlN/Al$_2$O$_3$ interface using the Fresnel equations for $s$- and $p$-polarized light:

$$R_s = \left| \frac{n_1 \cos \theta - n_2 \sqrt{1 - \left( \frac{n_1 \sin \theta}{n_2} \right)^2}}{n_1 \cos \theta + n_2 \sqrt{1 - \left( \frac{n_1 \sin \theta}{n_2} \right)^2}} \right|^2,$$

(2)

$$R_p = \left| \frac{-n_2 \cos \theta + n_1 \sqrt{1 - \left( \frac{n_1 \sin \theta}{n_2} \right)^2}}{n_2 \cos \theta + n_1 \sqrt{1 - \left( \frac{n_1 \sin \theta}{n_2} \right)^2}} \right|^2,$$

(3)

where $n_1$ and $n_2$ are the reflective indexes of Al$_2$O$_3$ and AlN, respectively. Using (2) and (3), we found that for $\theta = 45^\circ$ the reflection coefficient is 0.017 for $s$-polarization and only 0.0003 for $p$-polarization. Thus, $p$-polarized light should have an order of magnitude lower interference signal, which corresponds to our experimental results.
Figure 2 shows the results of band block fast Fourier transform (FFT) filtering in order to remove the interference harmonics. According to the intersubband transition selection rules, only \( p \)-polarized light (which has the polarization component along the structure growth axis) can be absorbed by QW layers. In order to estimate the intersubband absorption coefficient \( (\alpha_{QW}) \) of QWs, it is usually sufficient to normalize the intensity of \( p \)-polarized light \( (I_p) \) transmitted through the sample to that of \( s \)-polarized light \( (I_s) \), according to the Beer–Lambert–Bouguer law:

\[
\ln\left(\frac{I_p}{I_s}\right) = \ln(\exp[-(\alpha_p - \alpha_s)L]) = -(\alpha_p - \alpha_s)L = -\alpha_{QW}L,
\]

where \( L \) is the length of the optical path. However, equation (4) may not be entirely correct, because we should also take into account the polarization features of the experimental setup including light sources, mirrors and polarizers. Therefore, we additionally measured reference spectra of transmission for \( p \)- and \( s \)-polarization \( (I_p^0 \text{ and } I_s^0 \text{, respectively}) \) without a sample. The resulting spectrum of intersubband absorption derived by using the equation

\[
-\alpha_{QW}L = \ln\left(\frac{I_p/I_p^0}{I_s/I_s^0}\right)
\]

is shown in figure 3 (magenta line). The transmission spectra of the MQW structure at room temperature are also presented in figure 3 (black line). It should be noted that measurements at the temperature of liquid nitrogen (77 K) showed an insignificant blue shift (~2 meV) of the intersubband absorption peak.

![Figure 2](image1.png)

**Figure 2.** Intensity spectra of light of two polarizations, transmitted through the 1.8 nm-GaN/5 nm-AlN MQW structure at room temperature after band block fast Fourier transform (FFT) filtering.

![Figure 3](image2.png)

**Figure 3.** Intersubband transmission (black) and absorption (magenta) spectra of the 1.8 nm-GaN/5 nm-AlN MQW structure at room temperature.

A pronounced peak in the spectrum is associated with the intersubband electron transitions in GaN/AlN QWs. Our results can motivate the future research of GaN/AlN QWs aimed at the development of intersubband all-optical switches at telecommunication wavelengths. In general, such devices consisting of GaN/AlN QWs can be embedded into a ridge waveguide.

4. Conclusion

We investigated the room-temperature absorption spectra of a 1.8 nm-GaN/5 nm-AlN MQW structure for \( s \)- and \( p \)-polarizations of light. A single absorption peak was detected near the wavelength of the telecommunication optical window (1.55 μm). This peak is associated with intersubband electron
transitions in the QWs. A technique for the FFT filtering of intersubband absorption spectra is proposed to eliminate the parasitic interference special features.

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