Intersubband Absorption Saturation in AlN-based Waveguide with GaN/AlN Multiple Quantum Wells Fabricated by Metalorganic Vapor Phase Epitaxy

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***Abstract*—The intersubband absorption saturation in a ridge AlN-based waveguide with MOVPE fabricated GaN/AlN MQWs was examined. A 1.56-µm short-pulse laser with a temporal width of 0.4-ps FWHM and a repetition rate of 63 MHz was employed to elucidate a 5-dB saturation using a pulse energy of 115 pJ.**

Keywords—MOVPE, intersubbnd transition, GaN/AlN MQWs, absorption saturation

I. Introduction

The demands placed on optical communication bandwidth have propelled the research into high speed optical components including all-optical switches. Among the potential technologies, intersubband transition (ISBT) in GaN multiple quantum wells (MQWs) has the potential to answer this requirement. This is owing to the unique properties of nitride semiconductors especially ultrafast intersubband relaxation time promoting GaN-based all-optical switch which is capable for Tb/s data operating. So far, the optical switching utilizing the absorption saturation effect in GaN MQWs has been demonstrated only in molecular beam epitaxy (MBE) grown samples [1], [2]. Although metalorganic vapor phase epitaxy (MOVPE) can provide high-quality buffers favorable for low loss and good performance optical devices, the strong intersubband transition at communication wavelength, 1.55-µm, was only recently realized with MOVPE-grown GaN/AlN MQWs [3]. In this work, we demonstrate the intersubband absorption saturation in a ridge AlN-based waveguide with MOVPE-grown GaN/AlN MQWs.

II. Sample Preparation

A. Growth of Nitride Layers by MOVPE

The crystal growth of nitride semiconductors was done by AIXTRON 200/4 RF-S low-pressure MOVPE. Trimethyl-gallium, trimethyl-aluminium, ammonia and silane were used as gas precursors. The reactor pressure was maintained at 100 mbar during the growth. The sample was prepared on 0.4-µm-thick high-quality AlN buffer on a c-plain sapphire substrate. A 0.1- µm-thick AlGaN interlayer was grown on the top of the AlN buffer at 1150 °C followed by 10-period GaN/AlN MQWs (1.2 nm/3.0 nm) at 800 °C using pulse injection method [3]. To prevent the GaN/AlN MQWs from effects of sputtered Si_3N_4, the sample was capped with a 0.1-µm-thick AlN layer grown at 850 °C.

B. Waveguide Fabrication

In this work, sputtered Si_3N_4 was utilized as a cladding layer for AlN-based waveguide because of its properties: (i) transparent at 1.5-µm range, (ii) can be deposited at low temperature by sputtering method, and (iii) reflective index matching that of nitride semiconductor. A 0.5-µm-thick Si_3N_4 was deposited at 250 °C using Si target under Ar and N_2 ambient. After that, the 2-µm-wide ridge waveguide structure was fabricated by etching Si_3N_4 layer using ICP-RIE dry etching. The back-side of the sample was polished and a 400-µm-long waveguide was cleaved using a diamond pen.

III. Measurement Results

Prior to measurement, the functionality of fabricated waveguide was verified by observing a near-field image of propagating light from the output facet. The circular of light spot was observed confirming the successful fabrication. The polarization dependent loss (PDL) and the intersubband absorption saturation were evaluated.

A. Polarization Dependent Loss

The propagation spectra of TE- and TM-polarized light were investigated by direct coupling the signal from a supercontinuum light source covering 1.10 µm to 1.75 µm wavelength range to the ridge waveguide. At output facet, the propagating light was focused by a 100x lens and coupled to a large-diameter multimode fiber via a pinhole and a collimating lens. The polarization of light was controlled by placing a polarization filter between the 100x lens and the pinhole. The output light was then analyzed by optical spectrum analyzer. The PDL was defined by the ratio of transmittances of TE- and TM-polarized light and plotted as function of wavelength in Fig. 1. Note that, the noise around 1.75-µm wavelength was

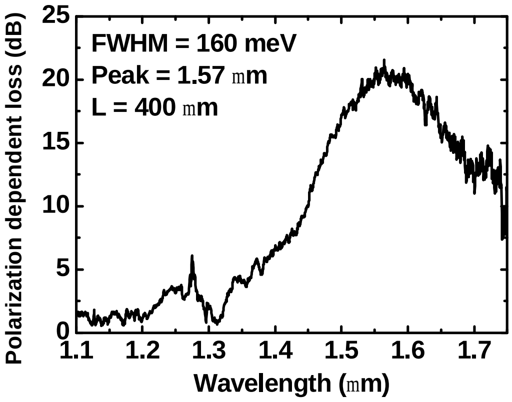

Figure 1. Polarization dependent loss defined by ratio of transmittances of TE- and TM-polarized light

originated from the limitation of the supercontinuum light source. From a 400-μm-long ridge waveguide, we could observe 20-dB PDL including absorption via intersubband transition. The inhomogeneous linewidth of PDL curve was 160 meV with an absorption peak at 1.57 μm. At short wavelength range, the PDL could also be observed. This TM-polarization loss was ascribed to edge dislocations in nitride semiconductors as supported by [4].

B. Intersubband Absorption Saturation

The intersubband absorption saturation in fabricated waveguide was evaluated by self-saturation measurement. A 1.56-μm-wavelength laser with a pulse full-width at half-maximum (FWHM) of 0.4 ps and a repetition rate of 63 MHz was directly coupled to the waveguide. The power of optical pulse was adjusted by an optical attenuator. The energy of input pulse could be determined by the average power of input pulse and repetition rate. The polarization of input light was controlled via fiber-type polarization controller. The output light from the waveguide was coupled to a multimode fiber using a 100x lanes, a pinhole and a collimating lens. The average power of output light was measured by a power meter. Therefore, the transmittances of both TE- and TM-polarized light could be determined by subtracting the output power with the input power (in dBm) and plotted as functions of input energy as presented in Fig. 2.

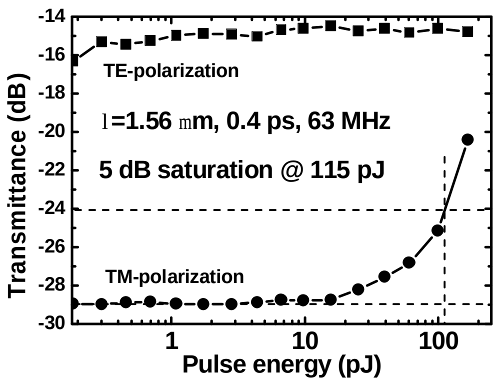

Figure 2. Transmittances of TE- and TM-polarized light as functions of input pulse energy.

For TE-polarization, the non-saturated loss was around 15 dB for a 400-μm-long ridge waveguide. Simulating by the beam propagation method, about 36% of input power can be guided in this ridge structure or 4.4-dB coupling loss equivalent (ideal case). The coupling loss at output facet to the multimode fiber was 9 dB estimated by fiber-to-fiber measurement. Hence, the loss 1.6 dB at most was the propagation loss and scattering loss at waveguide facets highlighting the capability of MOVPE-grown high-quality nitride layers for the fabrication of low loss devices. Considering TM-polarization, the optical nonlinearity via intersubband absorption was observed and 5-dB saturation level could be achieved by using an input energy of 115 pJ. However, this result cannot be directly compared with the records from MBE-grown GaN/AlN MQWs samples reported to have a 10-dB saturation using 38-pJ input energy [1] and a 5-dB saturation using 25-pJ input energy [2]. This is due to input pulse width of 0.4 ps in this work was relatively longer than that of 160 fs in [1] and that of 130 fs in [2]. The saturation energy in this work is expected to decrease with decreasing input pulse width as predicted from the simulation in [5].

IV. Conclusions

We have demonstrated the intersubband absorption saturation in ridge AlN-based waveguide with GaN/AlN MQWs fabricated by MOVPE. Pumped by 0.4-ps-FWHM pulse laser at 1.56-μm wavelength, 5-dB absorption saturation was achieved with 115-pJ of input pulse energy. This achievement has revealed the potential of MOVPE-grown GaN/AlN MQWs for intersubband optical devices capable of operating at communication wavelength.

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