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GaN-Based High-Speed Intersubband Optical Switches

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1. Introduction

Intersubband transition (ISBT) in semiconductor quantum wells (QWs) is a promising phenomenon for realizing high-speed all-optical switches since the absorption recovery time is extremely short due to the particularly fast carrier relaxation time. So far, ISBTs have been accomplished at optical communication wavelengths with QW structures such as InGaAs/AlAsSb [1], (CdS/ZnSe)/BeTe [2] and GaN/Al(Ga)N [3]. Above all, GaN QWs have several advantages, namely, 1) absorption recovery time is considerably below 1 ps, 2) the homogeneous spectral line width is sufficiently broad due to the short dephasing time, 3) a wide range of wavelengths is available with a less complicated QW structure, 4) the material is robust and less toxic, 5) two-photon absorption does not interfere with the saturable absorption due to the wide band-gap.

This paper reviews the authors' studies on the application of the ISBT in GaN QWs to high-speed optical switches. First, the relationship of the crystalline quality and the propagation loss in the device is discussed. Next, the absorption saturation is characterized at wavelengths of 1.4-1.7 μm. Then, the gate switch operations are verified utilizing two-color pump-probe method. Finally, the prospect of further improving the device performances is discussed.

2. Device Fabrication

Since ISBT occurs only for transverse magnetic (TM) polarization, the background propagation loss for TM polarization is crucial. Generally, a layer grown with molecular beam epitaxy (MBE) has many edge dislocations. The edge dislocations bring about excess polarization-dependent loss (PDL) for TM mode [4]. In our study, for the PDL to be suppressed, one sample had multiple AlN intermediate layers (MILs) as a dislocation filter and the others were grown on GaN or AlN buffer layers grown with metal-organic chemical vapor deposition (MOCVD).

The samples had a waveguide structure consisting of GaN or AlN layer on sapphire substrates. GaN/AlN multiple QWs (MQWs) were at the middle of the layer. The MQW structures were grown with MBE, since, until recently, ISBTs in GaN QWs were observed at optical communication wavelengths only with MBE-grown MQWs. Ridge or high mesa structures were fabricated by utilizing dry-etching technology.

3. Absorption Saturation

The absorption saturations were characterized by utilizing an optical parametric oscillator (OPO) with a repetition rate of 80 MHz and pulse width of 130 fs. The optical pulses were input to samples by polarization-maintaining dispersion-shifted fibers. In Fig. 1, the absorption saturation characteristics are plotted at wavelengths of (a) 1.7 and (b) 1.55 μm for samples with MQWs on MOCVD-grown GaN waveguides [5]. 10-dB saturations were achieved for both wavelengths.

In Fig. 1, the saturation characteristic is also shown at a wavelength of 1.43μm for a sample with MQWs on an MOCVD-grown AlN waveguide [6]. The absorption saturation by 7 dB was observed at pulse energy of 200 pJ. The absorption spectrum for the sample was not optimal for the measurements wavelength. This is a reason for the relatively high saturation energy. If the wavelength is optimal, the energy should decrease. This result leads to expectation that the AlN-waveguide structure realize optical switching at wavelengths of 1.3-1.5μm.

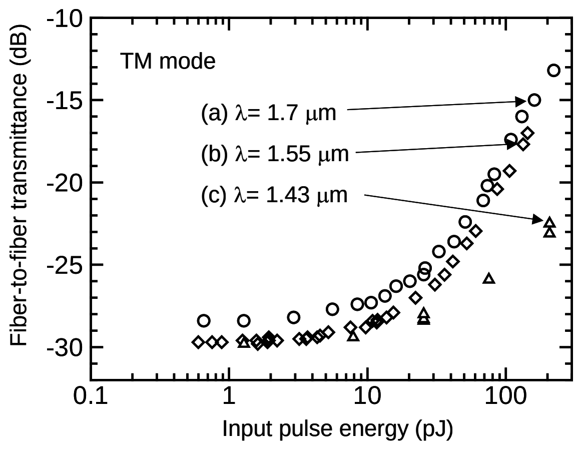

Fig.1 Characteristics of absorption saturation.

4. Gate Switch Operation

Gate switch operations were examined utilizing the signal (1.55 µm) and the idler (1.7µm) from the OPO. Fig. 2 (a) shows a gate-switch performance by the pump-probe technique for the sample grown on an MOCVD-grown GaN [7]. The wavelength and the energy of the control pulse were 1.7 µm and 150 pJ, and those of the signal pulses were 1.55 µm and 5 pJ, respectively. The extinction ratio was 11.5 dB and the gate window was as narrow as 230 fs.

Fig. 2 (b) shows the result of a pump-probe measurement with multiple probe pulses [7]. The measurements were carried out with the sample with MILs. The energy of the control and the signal pulses were 100 and 4 pJ, respectively. The signal pulse interval was as short as 0.67 ps. When the control pulse coincided with one of the signal pulses, the transmittance increased. This verifies that demultiplexing operation was accomplished for the pulse train with an interval of less than 1 ps.

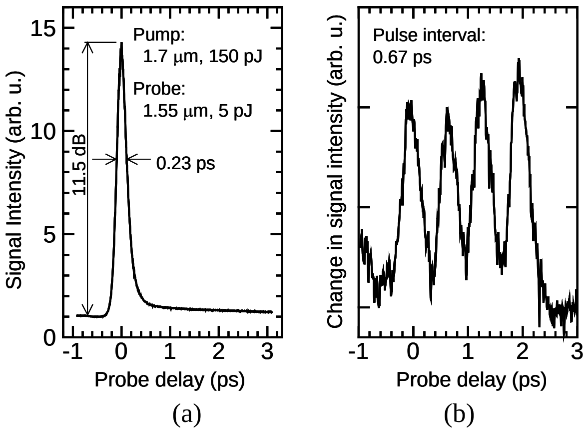

Fig. 2 (a) A gate switch operation with extinction ratio of 11.5 dB and gate width of 0.23 ps. (b) Response for signal pulse trains with an interval of 0.67 ps.

5. Prospect of Further Improving Performance

Although the ultrafast response was verified for GaN-ISBT optical switches, reduction of the high switching energy is prerequisite for practical use of the switch. Keys to reduction of the switching energy are to further decrease the excess PDL and to fabricate a waveguide with a smaller mode size [8]. Until recently, the excess PDL was 5-10 dB and the typical waveguide size was 1µm (width) x 2 µm (thickness). According to Ref.8, the 10-dB saturation will be achieved with pulse energy as low as 1 pJ when the excess PDL is suppressed and the cross-section of 0.8 µm x 0.8 µm is realized.

In Fig.3, the PDL for a recent sample with MQWs in an AlN waveguide is shown as a function of wavelength [9]. For the sample, the growth conditions were more carefully optimized. The waveguide size was 1µm (width) x 2 µm (thickness). The absorption at a wavelength of 1.5 µm is due to ISBT. The loss at a wavelength of 1.1 µm, at which wavelength ISBT should not occur, is as low as 1 dB. Thus, reduction of the background loss has been experimentally accomplished. In addition, an etching technique applicable to a smaller-size waveguide is developing [9]. Thus, high-speed optical switches with low operation energy will be realized in very near future.

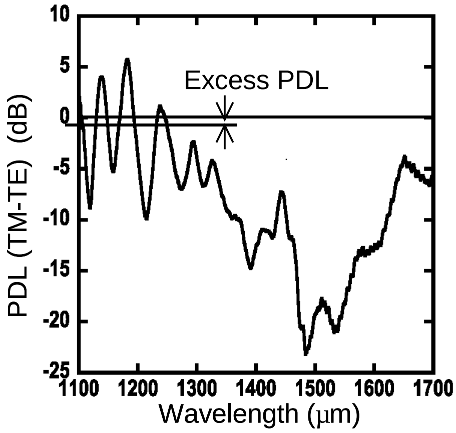

Fig. 3 PDL for a sample grown with carefully optimized growth conditions. The excess PDL is as low as 1 dB.

6. Summary

High-speed optical switches utilizing ISBTs in GaN QWs were investigated. Absorption saturation of more than 10 dB and ultrafast gate switch operations were verified. The prospect of further improving the device performance was also discussed.

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