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Improved Waveguide Structure for All Optical Switches based on Intersubband Transition in II-VI Quantum Wells

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1. Introduction

Short-wavelength intersubband traditions (ISBT) in semiconductors quantum wells (QWs) with ultra fast carrier relaxation (~1ps) has attracted much attention, especially by aiming at potential applications for all-optical signal processing for high-bit-rate (above 160 Gbit/s) optical fiber communication system at λ~1.55 μm. Recently, sub-ps all-optical modulation at optical communication wavelength have been demonstrated in ISBT-waveguide devices based on several material systems, such as InGaAs/AlAsSb [1], GaN/AlGaN [2], (CdS/ZnSe)/BeTe [3], where the operating energies to achieve 10 dB absorption saturation in these devices are 32 pJ, 100 pJ, and 13.1 pJ, respectively. However these figures are not sufficiently low for practical applications. The devices is intended to operate at high-bit-rate above 100 Gbit/s in optical communication systems. Thus the mean-operation-power will be a few or several tens watts, if the device is used with current performance in switching energy. This huge energy can not be accepted in practical use. Thus reduction of the operation energy is the most important issue for ISBT optical switches, where 10dB switching extinction ratio at 1pJ-input-energy is a mile stone to be achieved for practical application.

In this contribution, we report on the fabrication and characterization of II-VI-based ISBT waveguide devices with much improved switching energy, which is achieved by improved optical confinement in the waveguide. This is achieved by (1) employing a separate confinement heterostructure (SCH) which will make absorption saturation in the active layer more effective, and (2) narrow high-mesa waveguide in which its mesa width is reduced down to sub-μm range.

2. Fabrication of Waveguide Device

The schematic of cross-section of the waveguide structure is shown in Fig 1(a). A epitaxial-wafer of SCH structure consists of a 3-μm-thick $Zn_{0.67}Mg_{0.21}Be_{0.12}Se$ bottom cladding layer (CL, n=2.35) , a 0.28-μm-thick $Zn_{0.97}Be_{0.03}Se$ bottom optical confinement layer (OCL, n=2.45), 0.24-μm-thick (CdS/ZnSe)/BeTe MQW (n=2.54) active layer, a 0.28-μm-thick $Zn_{0.97}Be_{0.03}Se$ upper OCL and a 1-μm-thick $Zn_{0.67}Mg_{0.21}Be_{0.12}Se$ upper CL. These layers were grown sequentially on (001) GaAs homo-epitaxy substrate by dual chamber molecular beam epitaxy chamber. A active layer has 40 period of QWs which is designed such that 15-ML(mono layer)-thick BeTe barriers with ZnSe/CdS/ZnSe (1/~2/1 ML) well layers exhibit enough large ISB absorption at a wavelength of around 1.55 μm. A n-type doping is achieved by $ZnCl_2$ in the CdS/ZnSe well. The index contrast is as high as 0.2 or more between active and cladding layer. In addition, we employed high-mesa type waveguide which is more effective for an optical confinement than the ridge structure due to that lateral directions are cladding by air. Consequently, strong light confinement into active layer is achieved in this waveguide structure. For the fabrication process, we employed reactive ion etching in an inductive-coupled-plasma using Ar and BCl_3 gases. After fabricated the high-mesa structure, the sample wafer was cleaved to waveguide bars. Fig 1(b) shows the plan view of waveguide. The mesa patterns were tilted by 7.5° to reduce optical reflection from waveguide facets. In addition, both waveguide facets were coated by single SiO_2 layers that were used as anti-reflectors.

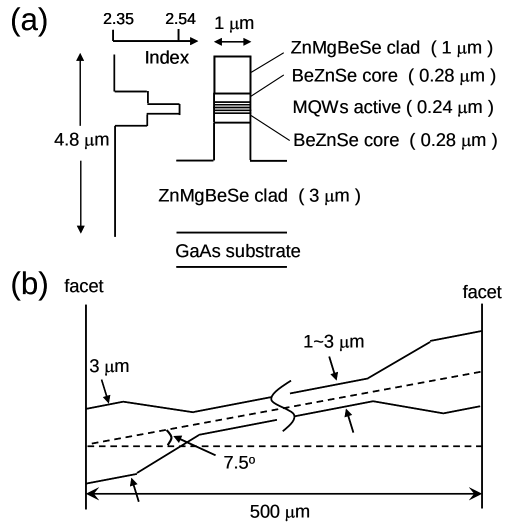

Fig. 1 Schematics of (a) cross-sectional and (b) plan view of waveguide structure.

3. Reduction of Operation Energy

To reduce operation energy, we employed SCH structure with narrow mesa width down to 1 μm. Since active layer is centered in a SCH structure, absorption saturation occurs effectively by use of the interaction with the highest light portion in waveguide mode. We estimated ~30 % reduction of saturation energy can be achieved in the SCH structure, compared with the non-SCH structure in which QWs are arranged homogeneously in the core part. In addition, the waveguide with narrow mesa is also used. Consequently, we can expect more efficient absorption saturation in waveguide structures with these improvement.

At first, we discuss the effect narrow mesa on ISB absorption saturation in waveguides. To measure absorption saturation, sub-ps optical pulse (pulse width = 0.3-0.4 ps) is injected into a waveguide with various mesa width through a tapered dispersion-shifted polarization-maintaining-fiber (DS-PMF). As a light source, an optical parametric oscillator (OPO) pumped by Ti:Sapphire mode-locked laser with repetition rate of 76 MHz was used. Fig 2(a) shows the insertion loss of the transverse magnetic (TM) polarization input as a function of input energy. The ISBT can be induced only by light with its electric field component along the growth direction i.e, TM polarization. The insertion loss decreases gradually with input pulse energy increasing. This is due to that ISB absorption saturation occurs for high input pulse energy. The 10-dB saturation energy as shown in the set in Fig 2(a) decreases from 15 pJ (3 μm mesa width) to 7 pJ (1 μm mesa width). It indicates that ISB absorption saturation occurred more effectively in the waveguide with narrow mesa due to strong confinement light into the core part. Then, we examined the dependence of input laser wavelength on the saturation energy. Fig 2(b) show the ISB absorption spectra of wafer and saturation energy for waveguide with mesa width of ~1 μm as a function of input laser wavelength. The saturation energy is sensitive of input wavelength and it is the lowest at the absorption peak. The 10-dB and 3-dB saturation energy are as low as 4 pJ and 1 pJ, respectively at 1620 nm, which is just resonant excitation with absorption peak. This result indicates that, to operate the device with lower switching energy at C-band wavelength, the absorption peak should be set to as near as 1550 nm.

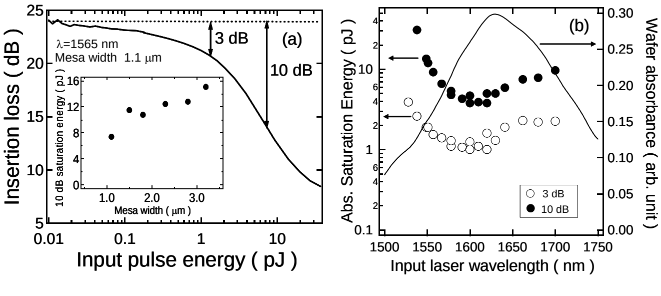

Fig. 2 (a) Absorption saturation results and 10 dB saturation energy as a function of waveguide mesa width, (b) ISB absorption spectra and saturation energy dependence of input laser wavelength.

4. Switching Characteristics

Finally, we discuss a recovery of absorption saturation which corresponds to gate time window for the ISBT switching device, by means of time-resolved-pump-probe experiment. The pump pulse at λ = 1565 nm, and the probe pulse at λ = 1630 nm, both of which generated synchronously from OPO, were used for the measurement. The pump and probe pulse energy are aligned with TM polarization and injected into the waveguide. Temporal change of transmission of probe pulse intensity is shown in Fig 3. The transmission change increased with pump pulse energy due to ISB absorption. A 10 dB extinction ratio is achieved by pomp pulse energy of 11.3 pJ. As the gate open time, the modulation band width of 0.36 ps (FMHW) is estimated which limited by time resolution of the measurement system. The real gate open time is as short as 0.2 ps, confirmed by previous report [3].

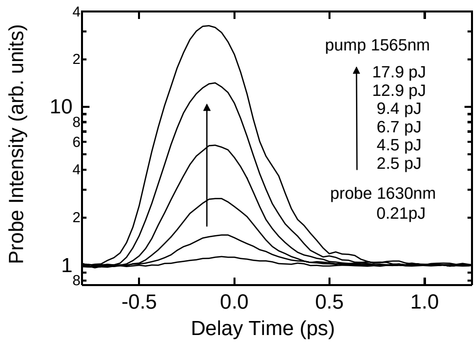

Fig. 3 Temporal change of transmitted probe pulse intensity.

Conclusions

By employing the SCH core structure with narrow mesa width (~1 μm), the 10-dB saturation energy are achieved by 7 pJ (1565 nm) and 4 pJ (1620 nm) input energy, respectively. As for switching characteristics, the gate window time is 0.36 ps (FMHW) which limited by time resolution of the measurement system. These results indicate that optical modulation up to 1 Tbit/s is possible in present II-VI-based ISBT waveguide.

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