# Ultrafast Intersubband All-Optical Switch in Wide-gap II-VI Quantum Well toward Lower Switching Energy Operation

R. Akimoto, G.W. Cong, K. Akita, T. Hasama, and H.Ishikawa

***Abstract*—We present an all-optical switch using intersubband transition in wide-gap II-VI-based quantum wells in an improved waveguide structure. The waveguide exhibits a separate confinement heterostructure (SCH) and sub-μm high-mesa waveguide for stronger optical confinement. A significant reduction is achieved in the control pulse energy while maintaining a sub-ps response. To further lower the energy, a coupled quantum well is proposed, and strong coupling was observed in intersubband absorption spectra.**

***Index Terms*—intersubband transition, ultrafast all-optical switch, II-VI, waveguide, couped quantum well**

## I. Introduction

RECENTLY, intersubband transition (ISBT) in semiconductor quantum wells (QWs) possessing ultrafast carrier relaxation (~1ps) and high conduction band offset has attracted considerable attention, since it can be utilized to realize all-optical switching and signal processing devices capable of high-bit-rate (above 100Gbit/s) operation at optical communication wavelengths. Such all-optical high-speed devices are required to expand the capacity of existing optical communication systems. In fact, sub-ps all-optical gate switching has been demonstrated in ISBT waveguide devices based on several material systems such as InGaAs/AlAsSb [1], GaN/AlGaN [2] and (CdS/ZnSe)/BeTe [3]. However, the switching efficiency is still not sufficiently low for practical application to signal processing operating at > 100Gbits/s, where an SER of > 10dB is required. The average power requirement for a device in which switching operations are performed at 100Gbits/s could exceed several watts, indicating that it exceeds the power tolerance of both the device and system. Therefore, a reduction in switching energy is imperative for practical applications. In this contribution, we report an improved switching performance of wide-gap II-VI-based ISBT waveguide devices[4], which is achieved by a stronger optical confinement in the waveguide structure. A very narrow high-mesa waveguide with a separate confinement heterostructure (SCH) is employed to reduce the switching energy.

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## II. Nonlinear Absorptive Waveguide

As shown in Fig. 1(a), a 3-μm-thick $Zn_{0.67}Mg_{0.21}Be_{0.12}Se$ bottom cladding layer (CL, n = 2.35), 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 multiple QW (MQW, n = 2.54) active layer, 0.28-μm-thick $Zn_{0.97}Be_{0.03}Se$ upper OCL and 1-μm-thick $Zn_{0.67}Mg_{0.21}Be_{0.12}Se$ upper CL were sequentially grown on a (001) GaAs homo-epitaxial substrate using a dual chamber molecular beam epitaxy system. The composition of the ternary and quaternary layers is adjusted to match the GaAs substrate lattice. The active layer has 40 QWs, each comprising a ZnSe(1ML: mono-layer) / CdS(~2ML) / ZnSe(1ML) well, doped with chlorine and sandwiched by 15-ML BeTe barrier layers. This QW structure results in a sufficiently high ISB absorption at the C and L bands [5]. A high-mesa structure with various mesa widths was fabricated employing a high-resolution photolithography using an i-line stepper and reactive ion etching in an inductively coupled high-density plasma using Ar and $BCl_3$ gases. For enhanced optical coupling between a fiber and a waveguide with a narrow mesa width, a tapered structure with a mesa width of 3μm is added at the input and output regions(Fig. 1(b)).

The ISB absorption saturation characteristics are investigated. Fig. 2(a) shows the TM insertion loss as a function of the input pulse energy ($\lambda_{in}$ = 1565nm) for the waveguide with a mesa width and device length of 1.1μm and 500μm, respectively. The insertion loss value for transverse-magnetic (TM) mode shows a distinct decrease and approaches the value for transverse-electric (TE) mode with an increase in the input pulse energy, indicating that ISB absorption saturation occurs with a high input energy. The 10-dB saturation energy is as low as 7pJ. The inset in Fig. 1 shows the 10-dB saturation energy as a function of the mesa width. As expected, a decrease in the saturation energy is

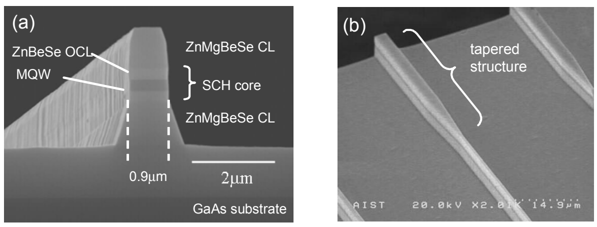


Fig. 1. Scanning electron microscope image of the waveguide. (a) Cross-sectional view of high-mesa SCH waveguide. (b) Tapered structure at the input/output port.

clearly observed as the mesa width is decreased.

We measured the recovery of absorption saturation, which corresponds to the gating time for the ISBT switch, by means of a time-resolved pump-probe experiment. The pump pulse at $\lambda$ = 1565nm and the probe pulse at $\lambda$ = 1630 nm were used for the measurement. The Temporal variation of transmission of probe pulse intensity is shown in Fig. 2(b). The transmission of the probe pulse reaches its maximum value at zero pump-probe delay time due to ISB absorption saturation caused by the pump pulse. The time response confirms an ultrafast gate window of 0.36ps (FWHM) in which the transmitted probe pulse is spectrally filtered to attain the highest SER and narrowest time window. The SER increases linearly with the control pulse energy at least up to ~20pJ. A 10-dB SER is achieved by a fibre input energy of 11.3pJ (1.13pJ/dB), indicating that a reduction of 39% in the switching energy was achieved when compared with that in our previous report (1.85pJ/dB).

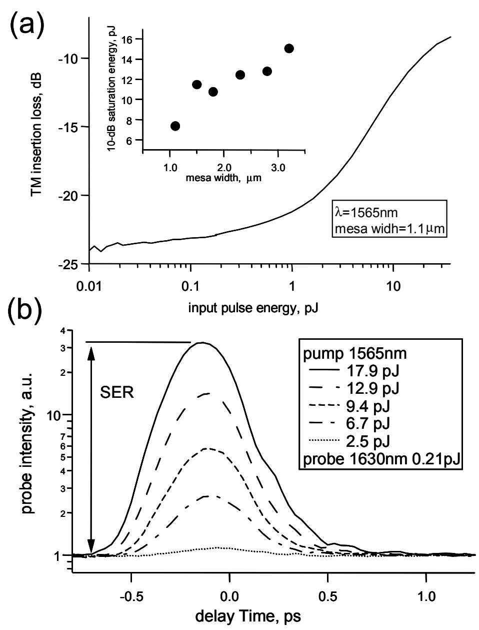


Fig. 2 . (a) TM insertion loss as a function of input pulse energy at $\lambda$= 1565nm for 1.1-µm mesa waveguide. Inset: input pulse energy necessary for absorption saturation of 10dB at $\lambda$= 1565nm. (b) Temporal variations of transmitted probe pulse intensity as a function of pump-probe pulse delay time for different pump pulse energies.

## III. Coupled Quantum Well

In general, $E_s = I_s \cdot \Delta t_p$, where $E_s$ and $I_s$ are the switching energy and the saturation intensity, respectively and $\Delta t_p$ is the pulse width that is usually fixed at ~0.1−1 ps for a bit rate in the range of 160 Gb/s−1 Tb/s. Then, $I_s$ is the target parameter that has to be decreased in order to decrease $E_s$. Since $I_s$ is inversely proportional to the square of the transition dipole and the relaxation time ($\tau$), the structure should be optimized to increase $\tau$ in order to obtain a lower $E_s$ without significantly affecting the transition dipole. By forming coupled quantum wells (CQW), we can introduce an immediate state whose coupling with the excited state determine $\tau$, while CQW structure can be adjusted such that the transition dipole between the ground and excited state does not change greatly. Sun *et al.* theoretically examined this approach in symmetric GaN/AlGaN CQW [6]. We apply the above idea to II-VI-based material system, and propose asymmetric double QWs coupled by a thin barrier, as shown in Fig. 3. In the strong coupling region in which a thickness of well 2 is ~10−12 ML, the e1-e3 transition is dominant in oscillator strength, and a switching performance could be adjusted for the operation at 160 Gb/s by utilizing the e1-e3 transition. On considering a structure for which the thickness of well 2 is 12 ML, $f_{13}$ = 0.64 and $\tau$ = 3 ps are evaluated. Accordingly, $E_s$ could be decreased to a third of that of single QWs.

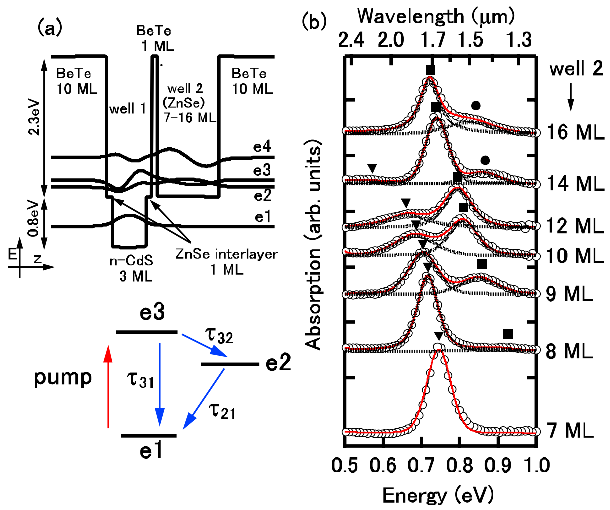


Fig. 3. (a) An intersubband dynamic scheme in II-VI-based CQW. (b) A representative self-consistent subband structure of CQW with layer parameters. (c) Intersubband absorption spectra (circles) with different well 2 thicknesses and the corresponding fitting spectra (the red solid lines denote the sum of the fitting components (dotted lines)). e1~e4 denotes the lowest electron states and $\tau_{32}$, $\tau_{31}$, and $\tau_{21}$ denote the scattering times. The markers (▼, ■, ●) respectively indicate the e1−e2, e1−e3 and e1−e4 transitions

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