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Intersubband Transition Based on a Novel II-VI Quantum Well Structure for Ultrafast All-optical Switching

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1. Introduction

In recent years, growing interest has been seen in intersubband transitions(ISB-T) in semiconductors quantum wells (QWs) at near-infrared (NIR) spectral region (λ<2 μm), especially aiming at potential applications for optical fiber communication systems around 1.55 μm wavelength [1-4]. The carrier relaxation between subbands is intrinsically ultrafast (sub ps to several ps) due to emissions of longitudinal optical (LO) phonons, when a subband spacing is larger than LO phonon energy. This property is quite feasible for ultrafast optoelectronic devices such as all-optical switches, modulators and amplifiers. To achieve short-wavelength ISBT less than 2 μm, material systems with large band offset have to be employed. So far, NIR wavelength ISBT and its ISB carrier relaxation times ranging from sub-ps to a few ps have been reported in material systems such as InGaAs/AlAs[1], InGaAs/AlAsSb[2] and GaN/AlGaN[3].

Recently, we have proposed another novel material system, ZnSe/BeTe, based on II-VI semiconductors for achieving NIR wavelength ISBT. This heterostructure has a large conduction-band offset (CBO) of ~2.3 eV for electrons in ZnSe layers[5], by which we actually demonstrated the ISB absorption as short as 1.6 μm covering the 1.55 μm wavelength within its spectral half width. In addition, we have also developed CdS/BeTe heterostructures, which has a huge CBO of 3.1eV to avoid a slow carrier relaxation process of Γ(ZnSe)–*X*(BeTe) transfer observed in ZnSe/BeTe[6]. For future device applications, the confinement of the infrared light into active layers is important point for reducing an optical gate switching power for all-optical switching device. As a material of cladding layer, ZnMgBeSe can be employed, since the band gap of this material can be tuned from 2.7 to 4.5 eV with matching a lattice constant to GaAs substrate. As for switching time, these II-VI structures take advantage of their higher ionicity, regarding the ultrafast carrier relaxation. Since the ISB relaxation process is controlled mainly by the Fröhich interaction between electrons and LO phonons, a faster relaxation is expected for a material with higher ionicity.

2. Experimental

The (CdS/ZnSe)/BeTe QWs samples were grown on undoped (001)-oriented GaAs substrates by molecular-beam epitaxy in a dual-chamber system. After a 250 nm-thick GaAs buffer layer was grown in a III-V chamber to improve the quality of the GaAs surface, the sample was transferred through ultra-high-vacuum transfer modules into a II-VI chamber for the growth of (CdS/ZnSe)/BeTe QWs. To access ISBT, samples were fabricated to form a multi-pass waveguide for near-infrared radiation. The details for the waveguide fabrication have been reported elsewhere. Time-resolved one-colour pump and probe experiment was performed at room temperature in order to measure the ISB carrier relaxation time. As a light source, we used an optical parametric amplifier (OPA) pumped by a Ti: sapphire amplifier that delivers ~120 fs pulses at a repetition rate of 1 kHz with a time-resolution of ~150 fs.

3. ~1.55 μm ISB absorption and waveguide structures

Figure 1 shows the polarization-resolved intersubband absorption spectra in the CdS/ZnSe/BeTe structure, which is composed of 40-period CdS/ZnSe/BeTe quantum well separated by 25ML-thick ZnSe spacer layer. Each quantum well is composed of a 2.5ML-thick CdS well layer, 10ML-thick BeTe barrier layers and 1ML-thick ZnSe interface layers between CdS and BeTe. We have set thicker BeTe barriers in the present structure than that in structures reported previously (4-5 ML thick BeTe)[7] to achieve a sufficient quantum confinement for the second subband. The absorption peak is as short as 1.59 μm with its half width of 190 nm, covering the important 1.55 μm wavelength within its absorption band. The detail of structural dependence on ISB absorption will be presented.

For future device applications, the confinement of the infrared light into active layers using ridge-waveguide structure is an important point for reducing an optical gate switching power in all-optical switching device. As a material of cladding layer, ZnMgBeSe can be employed, since the band gap of this material can be tuned from 2.7 to 4.5 eV with matching a lattice constant to GaAs substrate. For a design of waveguide, refractive indices of materials are of crucial importance. We have estimated wavelength dependence of refractive indices of CdS/ZnSe/BeTe active and ZnMgBeSe cladding layers by means of the optical reflectivity of thin film samples. The refractive indices of CdS/ZnSe/BeTe active and $(Zn_{0.68}Mg_{0.2}Be_{0.12})Se$ (Eg=3.2eV.) cladding layers are found to be 2.45 and 2.31 at λ=1.55 μm, respectively, indicating that an enough optical confinement can be achieved. We have also fabricated a slab-type waveguide structure as shown in Fig. 2. A two-dimensional crystal growth was always kept

during the MBE deposition, indicating that waveguide is of high structural quality. An ICP(inductively coupled plasma) reactive ion etching process using Ar and BCl_3 gasses will be used to fabricate a ridge structure on slab waveguide.

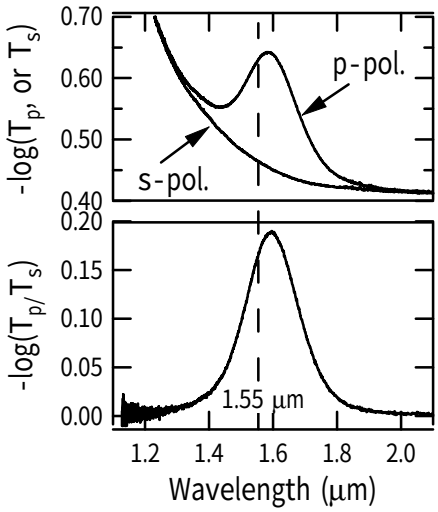

Fig. 1 Intersubband absorption in (CdS/ZnSe)/BeTe quantum wells with multipass waveguide geometry

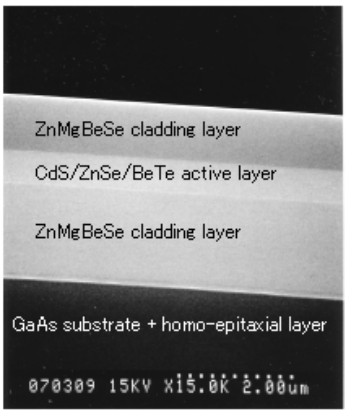

Fig. 2 Cross sectional SEM image of slab waveguide structure

4. Ultrafast ISBT Switching Response

Figure 3(a) shows the temporal changes of ISB absorption bleaching in three samples of the (CdS/ZnSe)/BeTe QWs exhibiting different peak absorption wavelength, measured by one-colour pump and probe experiment[7]. The pump pulse energy is 10~20 μJ/cm^2 in front of the samples. The data for ZnSe/BeTe QWs are also shown in Fig. 3(b), which are the same as those already reported previously[6]. For comparison, data on both sides, which have peak absorption wavelength similar to each other, are arranged. In the absorption recovery in ZnSe/BeTe QWs, a contribution of the slow component with a time constant of a few ps increases with decreasing the ISBT wavelength. The slow component eventually becomes a dominant decay process at the ISBT wavelength of 1.8 μm, since the energy of the second subband becomes comparable to that of *X* state in BeTe barrier, and the carrier relaxation process is mediated by the Γ(ZnSe)-*X*(BeTe) electron transfer[7]. On the other hand, the slow component is not observed in the ISB absorption recovery in (CdS/ZnSe)/BeTe QWs. The absorption recovers almost within 1 ps, where time constants defined by 1/e decay are 160, 240, and 270 fs in samples with peak absorption wavelength of 2.22, 1.96, and 1.82 μm, respectively. In (CdS/ZnSe)/BeTe QWs with ISBT wavelength of 1.82 μm, the energy of second subband locates by at least ~0.3 eV below that of *X* state in BeTe barrier with keeping ISBT wavelength at near-infrared region. Therefore, the Γ-*X* electron transfer is completely suppressed in (CdS/ZnSe)/BeTe structures, as expected from the band alignment.

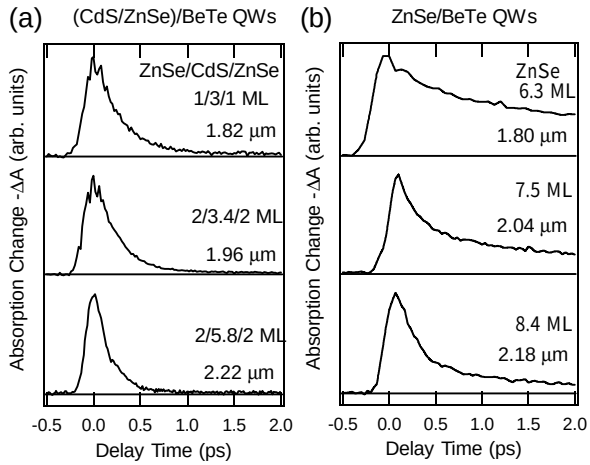

Fig. 3 Temporal changes in intersubband absorption bleaching for samples with (a) (CdS/ZnSe)/BeTe and (b) ZnSe/BeTe quantum wells (QWs) structures, taken by one-color pump and probe experiment. The peak wavelength of the ISB absorption and structural parameter in a well layer for each sample are indicated in each panel.

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