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InGaAs-Based Quantum Wells for Ultrafast All-Optical Switches Using Intersubband Transitions

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1. Introduction

The ever-increasing demand for capacity in optical transmission systems, corresponding directly to the explosive growth of the internet, calls for an integration of faster time-division multiplexing (TDM) and denser wavelength-division multiplexing (WDM) technologies. Systems with single-transmission rates above 100 Gbit/s require optical time division multiplexing (OTDM) technologies due to the response speed limitations of electronic devices. To realize such OTDM systems, we need ultrafast all-optical switches for functions such as optical multiplexing, demultiplexing, pulse regeneration, and retiming.

Absorption saturation associated with the intersubband transitions (ISBT) in doped quantum wells (QWs) is one of the most promising candidates for realizing all-optical switches due to its ultrafast relaxation times and large optical nonlinearities. Recently, several groups have achieved sub-picosecond response times for ISBT near-communication wavelengths using InGaAs/AlAsSb coupled double quantum wells (CDQWs) (FESTA) [1], GaN/Al(Ga)N QWs (Lucent and Sophia Univ.) [2,3], and ZnSe/BeTe QWs (AIST) [4]. Among these QW systems, InGaAs/AlAsSb CDQW is the best-suited for ultrafast all-optical switches due to its potential for realizing low switching energy.

To achieve the transition energy required for communication wavelengths, well widths should be very narrow, usually from 6 to 9 monolayers (MLs), meaning that even a single ML fluctuation in the well width will cause a significant shift in transition energy. In QWs, especially narrow ones, interfaces play an important role in optical and electrical properties. The high doping in InGaAs/AlAsSb QWs degrade the structure due to exchange reactions and interdiffusion of constituent species. We have greatly improved QW properties by inserting a few mono-layers of AlAs between the InGaAs well and the AlAsSb barrier, thereby achieving extremely high absorption coefficients and ultralow intersubband absorption saturation intensity (the latter is related to switching power) [5].

In this paper, we will review recent results on the optical and structural properties of novel strain-compensated InGaAs/AlAs/AlAsSb CDQWs grown by molecular beam epitaxy, as well as results on the linear and nonlinear optical responses of ISBTs.

2. Sample growth and characterization

InGaAs/AlAs/AlAsSb CDQWs were grown on Fe-doped (001) InP substrate by solid source molecular beam epitaxy (MBE). Elemental Ga, In, and Al were used for the group III growth species, and Sb_2 and As_2 were used for the group V growth species. As_2 was supplied using a valved cracker cell. The InGaAs wells were doped with Si. The structural quality of the QWs was examined by 4-crystal x-ray diffraction rocking curve measurements made with a Philips MRD system and high-resolution transmission electron microscopy (HRTEM).

Our goal is to fabricate ridge-waveguide switches. The small refractive index of the AlAs layer tends to make waveguides leaky. In fact, computer simulations of waveguide structures with InAlAs cladding layers revealed that the waveguide with AlAs stopping layers in the previous CDQW structure [6] was leaky. To enhance optical confinement in the waveguide core, we modified the CDQWs structure as follows: (1) the thickness of the AlAsSb barrier layers was reduced; (2) the In composition and layer thickness in the InGaAs wells were increased; and (3) the stack period of the CDQWs was increased. Figure 1(a) and (b) show the typical waveguide structure. The CDQWs sample is doped in the well to about 4×10^{18} cm^{-3} and has 40 periods of 4-nm $AlAs_{0.56}Sb_{0.44}$/4-ML AlAs/2.6-nm InGaAs/3-ML AlAs/2.6-nm InGaAs/3-ML AlAs/ 4-nm $AlAs_{0.56}Sb_{0.44}$. The InAlAs cladding layer was lattice-matched to the InP substrate. AlAs thickness and InGaAs composition and thickness were optimized to minimize the misfit strain caused by AlAs layer and to achieve 1.55 μm ISBT [7]. The x-ray rocking curve of this CDQWs sample is shown in Fig. 2. Extended satellite peaks confirm the high crystalline quality.

3. Response Measurements

The ISB absorption spectra were measured using p-polarized light in a Fourier-transform infrared (FTIR) spectrometer (Bruker 66V/S FTIR). The dependence of sample transmissivity on input pulse energy was measured using either an optical parametric oscillator (OPO; 80-MHz repetition rate, 300 fs pulse width) or optical parametric amplifiers (OPA; 1 KHz repetition rate, 150 fs pulse width and 100 kHz repetition rate, 90 fs pulse width).

CDQWs have four subbands in the conduction band (see Fig. 1 (b)), and our design of QWs is such that the

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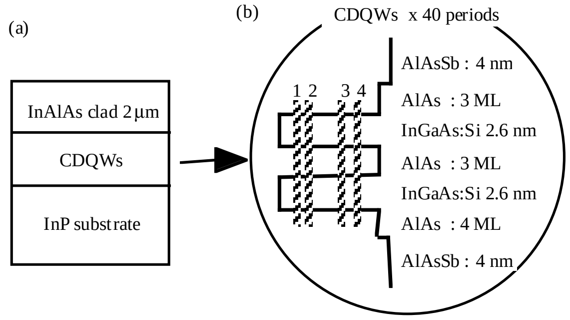

Fig. 1 (a) Schematic of sample layer structure, (b) conduction band alignment of InGaAs/AlAs/AlAsSb CDQWs with AlAs layers.

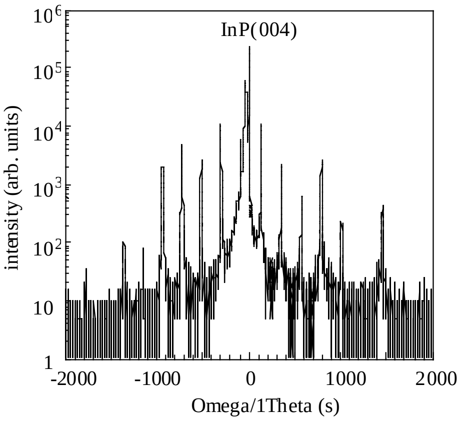

Fig. 2 XRD rocking curve of InGaAs/AlAs/AlAsSb CDQW waveguide structure

wavelength of the 1-4 transition becomes the 1.55-μm optical communication wavelength. The FTIR spectrum of the present sample (not shown) shows three absorption peaks corresponding to 1-4, 1-3, and 2-3 transitions. The absorption peak of the 1-4 transition is located around the communication wavelength. The observed 1-3 transition indicates that the CDQWs are not a symmetric double QWs. This can be attributed to interdiffusion of constituent species during MBE growth of heterointerfaces.

To determine the response time for absorption saturation, we performed a pump-probe measurement using the multipass waveguide sample. In this measurement, we measured the time evolution of the wavelength-integrated interband absorption induced by intersubband excitation in the CDQW sample (see the inset for Fig. 3). The response time is estimated to be 600 fs [7], corresponding to previous results of CDQWs [6].

Practical switches require switching energies somewhere around several pJ or less, depending on the operating speed of the system. Current ISBT switches require gate pulses of 10 to 30 pJ [6, 8]. To further reduce switching energy, CDQW parameters, waveguide design, and operation conditions are being optimized.

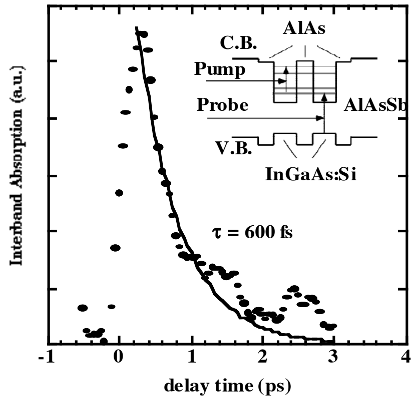

Fig. 3 Time evolution of wavelength-integrated interband absorption induced by intersubband excitation in the CDQW sample. The solid line indicates an exponential decay curve with a decay time of 600 fs. The inset shows band alignment of a CDQW structure

4. Conclusion

The foregoing summarizes recent attempts to realize ultrafast all-optical switches using ISBTs of InGaAs/AlAs/AlAsSb strain compensated CDQWs. Although the structural quality of the CDQWs sample is greatly improved by optimizing CDQWs parameters, further refinements in growth conditions will be necessary to realize truly symmetric double QWs. To realize practical switches, further optimization of CDQWs parameters, waveguide design, and operation condition are necessary.

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