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Electrorefractive Effect in Strained InGaAs/InAlAs Five-Layer Asymmetric Coupled Quantum Well

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1. Introduction

Semiconductor optical modulators and switches based on phase modulation such as Mach-Zehnder (MZ) modulators are becoming more and more important in optical fiber communications. For high-performance optical modulators and switches based on phase modulation, a large electrorefractive index change Δn with a small absorption loss is necessary in quantum wells (QWs). A five-layer asymmetric coupled quantum well (FACQW) [1-4] is one of the most promising candidates for producing a giant electrorefractive index change. So far, we studied the lattice-matched FACQW, but if a strain effect is introduced to the FACQW, its electrorefractive index change may be improved.

In this paper, we propose an InGaAs/InAlAs strained FACQW for optical modulators based on phase modulation, and theoretically analyzed its electrorefractive effect. It was found that the electrorefractive index change in the FACQW can be improved by using strained structure to the FACQW.

2. InGaAs/InAlAs Strained FACQW Structure

Figure 1 shows the proposed InGaAs/InAlAs strained FACQW structure. It is composed of 21-monolayer (ML) quantum well (QW1), 11-ML barrier layer and 20-ML (4+16) quantum well (QW2). The 4-ML barrier layer in QW2 is inserted for potential modification. $In_{0.51}Ga_{0.49}As$ well layers are intentionally strained tensilely (0.15 %) to an InP substrate to decrease the energy gap between HH2 and LH1 at electric field F=0 kV/cm. Its reason is described in the next section. $In_{0.54}Al_{0.46}As$ barrier layers are compressively strained (0.11 %) to a substrate, thus this is so-called “strain-balanced structure”.

Figure 2 shows the field-induced variation of wavefunctions for an electron, a light hole and a heavy hole. To show the movement of wavefunctions which mainly contribute to the absorption change, the wavefunctions of HH2 (the first excited state of the heavy hole) at wavenumber k =0, and that of LH1 (the ground state of the light hole) at k= $0.007\times k_0$ ($k_0=2\pi/a_0$, a_0=0.293 nm) are shown. On the other hand, E1 (the ground state of the electron) moves almost the same way at k=0 and $k=0.007\times k_0$, so it is described by one line. When the applied electric field F is changed from −24 kV/cm to −32 kV/cm, the wavefunction of E1 equally distributed among QWs, moves to QW2 and the overlap integral of E1 and HH2 increases. As the applied electric field is changed from −32 kV/cm to −37 kV/cm, the wavefunction of LH1 moves from QW1 to QW2, and the overlap integral of E1 and LH1 increases. Due to the increase of overlap integral, absorption caused

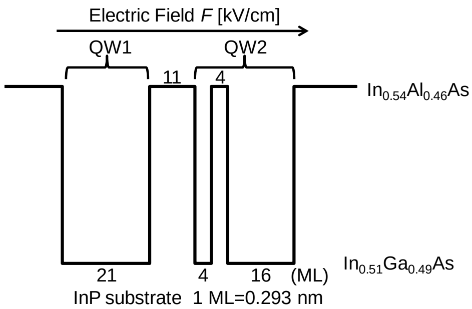

Fig.1. Schematic potential diagram of the proposed InGaAs/InAlAs strained FACQW for 1.55 μm wavelength.

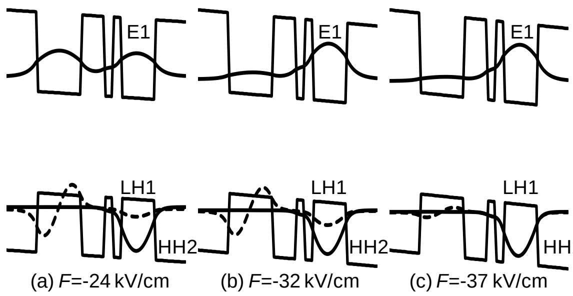

Fig.2. Wavefunction distributions of an electron and holes in the InGaAs/InAlAs strained FACQW under various electric field.

by transition gets very large from F=–24 kV/cm to F=–37 kV/cm.

3. Electrorefractive Effect in Strained InGaAs/InAlAs FACQW

The absorption coefficient spectra of the FACQW were calculated by solving the Schrödinger equations utilizing the $k\cdot p$ perturbation theory with a 4×4 Luttinger-Kohn Hamiltonian[5]. The analyses took into account the effect of valence band mixing, and the effect of excitons using the non-variational approach.

Figure 3 shows a calculated absorption coefficient spectra of the InGaAs/InAlAs strained FACQW. The peaks at 1362 and 1428 nm come from excitons regarding E1-LH1 and E1-HH2 transitions, E2-HH1 transition, respectively. With the increase of the electric field, the absorption peak at 1362 nm increases without red shift and this is a unique behavior of the quantum-confined Stark effect (QCSE) of the FACQW compared with rectangular quantum wells (RQWs).

Figure 4 shows a calculated electrorefractive index change Δn of the InGaAs/InAlAs strained FACQW (solid line) as a function of applied electric field and that of the lattice matched FACQW[4] (dashed line). This was calculated by using Kramers-Kronig relation. Through the relation, the large absorption coefficient change $\Delta\alpha$ of the FACQW brings about a large Δn in the transparent wavelength region. The electrorefractive sensitivity $|dn/dF|$ of the strained FACQW at F=–24 to –37 kV/cm is approximately 5.9×10^{-4} cm/kV and this value is about three times larger than that of lattice-matched FACQW at F=–24 to –60 kV/cm, resulting in lower voltage operation for phase modulation. The linearity of electrorefractive index change by electric field was also improved.

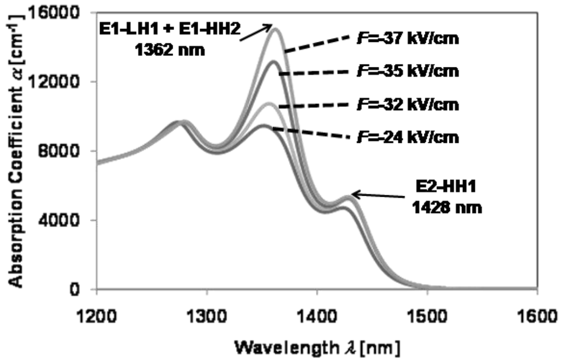

Fig.3. Calculated absorption spectra of InGaAs/InAlAs Strained FACQW (TE mode) (F in kV/cm).

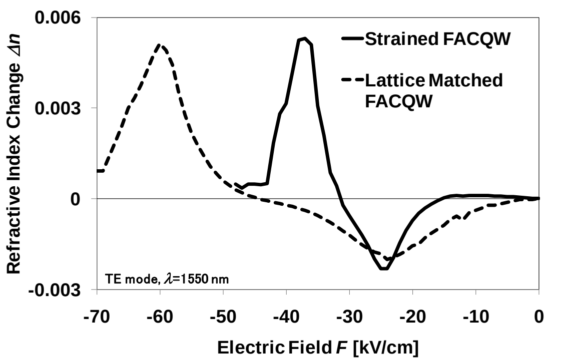

Fig.4 Calculated electrorefractive index change Δn (TE mode) of InGaAs/InAlAs strained FACQW (solid line) and lattice-matched FACQW (dashed line) at 1550nm.

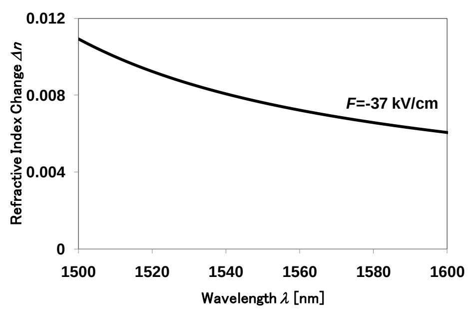

Fig.5 Calculated wavelength dependence of electrorefractive index change Δn in InGaAs/InAlAs strained FACQW when electric field is changed from -24 to 37 kV/cm (TE mode).

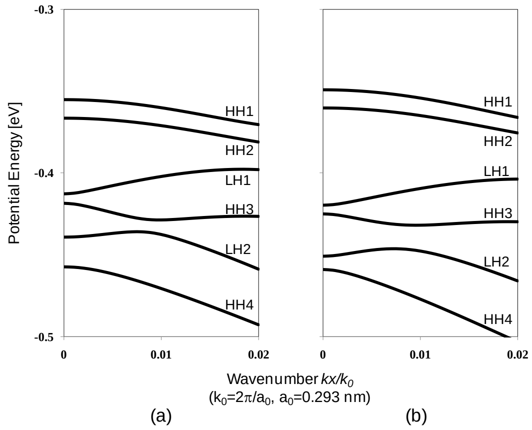

Fig.6 Valence band dispersion (electric field F = 0 kV/cm) for (a) InGaAs/InAlAs strained FACQW, and (b) InGaAs/InAlAs lattice matched FACQW.

Figure 5 shows the dependence of electrorefractive index change on wavelength when the electric field is changed from F=–24 to –37 kV/cm. The large electrorefractive index change can be obtained over a wide wavelength range for 1.55 μm wavelength region away from absorption edge (1428 nm), and such characteristic is very useful for low-voltage and high speed optical modulators and switches based on phase modulation.

Valence band dispersions of the InGaAs/InAlAs strained and lattice-matched FACQWs at F=0 kV/cm are shown in Fig. 6. All bands have almost the same energy for both, but in the case of the strained FACQW, bands are closely positioned due to the applied tensile strain to well layers. The absorption increase of FACQW results from movement of HH2 and LH1 wavefunctions. With tensile strain and modification of structure, bands of HH2 and LH1 have closer energy than lattice-matched FACQW, thus absorption peak increases at smaller electric field and a large electrorefractive index change can be obtained at lower voltage.

4. Conclusions

The electrorefractive effect in an InGaAs/InAlAs strained FACQW for 1.55-μm wavelength regions was discussed. The strained FACQW is expected to exhibit larger electrorefractive index change over a wide wavelength range than the lattice-matched FACQW. The strained FACQW is a promising structure for low-voltage and high speed optical modulators and switches based on phase modulation.

Acknowledgements

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