Electrorefractive Effect in Asymmetric Triple 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 $\Delta n$ with a small absorption loss is necessary in quantum wells (QWs). A five-layer asymmetric coupled quantum well (FACQW) [1-3] is one of the most promising candidates for producing a giant electrorefractive index change. We also proposed an asymmetric triple coupled quantum well (ATCQW) where abrupt electrorefractive index change occurs under a very small electric field[4]. The ATCQW is a modified structure of the FACQW. However, operation mechanism of the ATCQW is different from that of the FACQW.

In this paper, we discuss the electrorefractive effect in a GaAs/AlGaAs ATCQW for 0.9-μm and InGaAs/InAlAs ATCQW for 1.55-μm-wavelength regions.

2. Electrorefractive Effect in GaAs/AlGaAs ATCQW

Figure 1(a) illustrates a proposed GaAs/AlGaAs ATCQW structure. The thicknesses of GaAs well layers are 20, 13, 12 ML, respectively, and they are thicker than those of the GaAs/AlGaAs FACQW[1]. We therefore call this structure an asymmetric “triple” coupled quantum well.

Figure 2 shows the field-induced variation of wavefunctions for an electron and a heavy hole. When the applied electric field $F$ is changed from 40 kV/cm to 50 kV/cm, the wavefunction of HH2 moves from QW1 to QW2 and QW3. The wavefunction of HH2 distributes point-symmetrically in QW2 and QW3 with the AlGaAs layer as the center. At $F=40$ kV/cm, the absorption due to E1-HH2 transition is large because of its large overlap integral, but at $F=50$ kV/cm, the absorption due to the E1-HH2 transition is quite small. This is because the overlap integral of the E1-HH2 transition is small due to the point-symmetrical distribution of HH2.

Figure 3(a) shows a calculated absorption coefficient spectra of the GaAs/AlGaAs ATCQW. The peaks at 789, 801, 811 nm come from excitons regarding E2-LH1 transitions, E2-HH1 transition, E1-HH2 transition, respectively.

The result of photocurrent measurement current measurements for TE mode light is also shown in Fig. 3(b). The sample was grown using molecular beam epitaxy (MBE) method. The calculated results are quite consistent with the experimental ones.

Figure 4 shows a calculated electrorefractive index change $\Delta n$ of the GaAs/AlGaAs ATCQW as a function of applied electric field. The index change for a rectangular QW (RQW) with the same wavelength of the absorption edge with the ATCQW is also shown for comparison. In the case of the ATCQW, giant electrorefractive index change $\left|\frac{dn}{dF}\right|$ of $6.3 \times 10^{-4}$ cm/kV can be obtained at $F=40$ kV/cm in the wavelength region away from absorption edge. These characteristics are very useful for low-voltage and high speed optical modulators and switches based on phase modulation.

3. Electrorefractive Effect in InGaAs/InAlAs ATCQW

Figure 1(b) illustrates the proposed In0.53Ga0.47As/In0.52Al0.48As ATCQW for 0.9 μm and In0.55Ga0.45As/In0.51Al0.49As ATCQW for 1.55 μm-wavelength regions.
In0.52Al0.48As ATCQW structure for 1.55 μm wavelength region. All layers are lattice-matched to an InP substrate.

Valence band dispersions of the InGaAs/InAlAs ATCQW and conventional RQW are shown in Fig. 5. They were calculated by solving the Schrödinger equations utilizing the \( k \cdot p \) perturbation theory with a 4 x 4 Luttinger-Kohn Hamiltonian[5]. The HH1 band has almost the same energy for both, but in the case of ATCQW, higher bands are closely positioned due to the coupled QW structure.

Figure 6 shows the calculated distributions of wavefunctions for an electron and a heavy hole at wavenumber \( k = 0.006 \times (2\pi/a_0) \) under various electric fields. When the applied electric field is changed from 40 kV/cm to 45 kV/cm, the wavefunction of HH3 (the second excited state of the heavy hole) moves from QW 2 to QW1 and QW3, but the overlap integrals of E1-HH3, E2-HH3 are quite small and negligible. As the electric field increases to 50 kV/cm, the wavefunction of HH3 moves to QW1, and the overlap integral of E1-HH3 increases, resulting in large absorption. It should be noted that there is no change in the wavefunction distribution for \( k = 0 \).

The calculated absorption spectra and the dependence of electrorefractive index change on electric field are shown in Fig. 7. At around \( F = 45 \) to 50 kV/cm, the absorption at 1380 nm increases due to the E1-HH3 transition at \( k \neq 0 \), causing large positive change in refractive index. The refractive index change \( |dn/dF| \) at \( F = 45-50 \) kV/cm is as large as \( 1.3 \times 10^{-3} \) cm/kV which is three times larger than that of InGaAs/InAlAs FACQW. But unfortunately the region of electric field for large electrorefractive index change is relatively narrow, so further improvement is needed for practical use.

4. Conclusions

The electrorefractive effect a GaAs/AlGaAs ATCQW for 0.9-μm and InGaAs/InAlAs ATCQW for 1.55-μm wavelength regions are discussed. The ATCQWs are expected to exhibit electrorefractive index change larger than that in the FACQW. The ATCQW is a promising structure for low-voltage and high speed optical modulators and switches based on phase modulation.

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