P-7-12

Extended Abstracts of the 2009 International Conference on Solid State Devices and Materials, Sendai, 2009, pp532-533

Electrorefractive Effect in Asymmetric Triple Coupled Quantum Well

Kenji Ema[1], Wataru Endo[1], Taro Arakawa[1], and Kunio Tada[2]

[1]Graduate School of Engineering, Yokohama National University
79-5 Tokiwadai, Hodogaya-ku, Yokohama 240-8501, Japan
Phone: +81-45-339-4143 E-mail: arakawa@ynu.ac.jp
[2] Graduate School of Engineering, Kanazawa Institute of Technology
1-3-4 Atago, Minato-ku, Tokyo 105-0002, Japan

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) [1-3] 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 QW 1 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 photoabsorption 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 culculated electrorefractive index change Δn 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

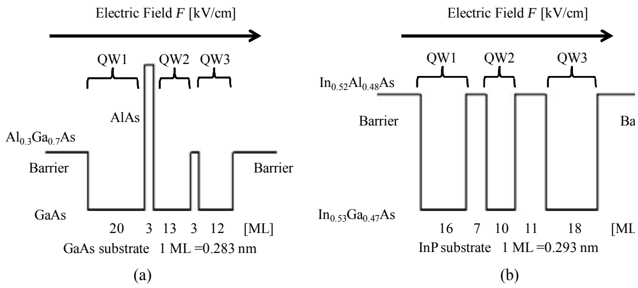

Fig.1 Schematic potential structure of (a)GaAs/AlGaAs ATCQW for 0.9 μm. (b) InGaAs /InAlAs ATCQW for 1.55 μm.

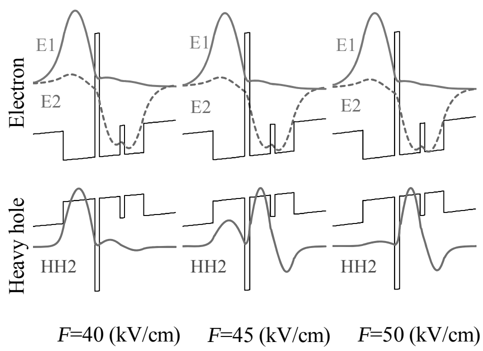

Fig.2 Wavefunction distributions in the GaAs/AlGaAs ATCQW.

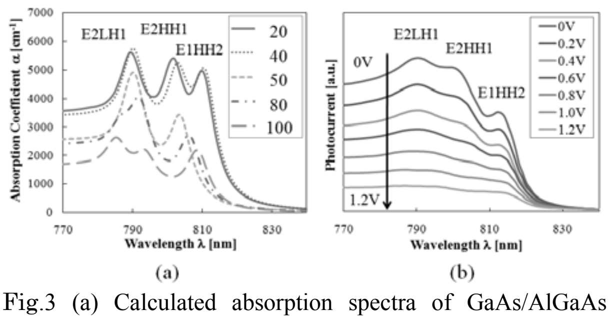

Fig.3 (a) Calculated absorption spectra of GaAs/AlGaAs ATCQW (TE mode) (F in kV/cm). (b)Measured photoabsorption current spectra at room temperature (TE mode).

edge with the ATCQW is also shown for comparison. In the case of the ATCQW, giant electrorefractive index change $|dn/dF|$ of 6.3×10^{-4} cm/kV can be obtained at around 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 $In_{0.53}Ga_{0.47}As$

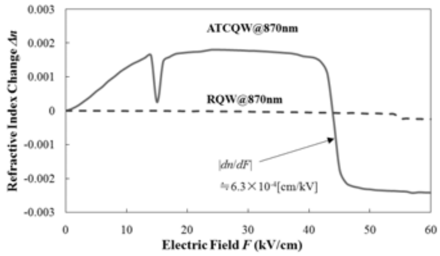

Fig.4 Calculated electrorefractive index change Δn (TE mode) of GaAs/AlGaAs ATCQW at 870nm, and GaAs/AlGaAs rectangular QW (20ML) at 870nm.

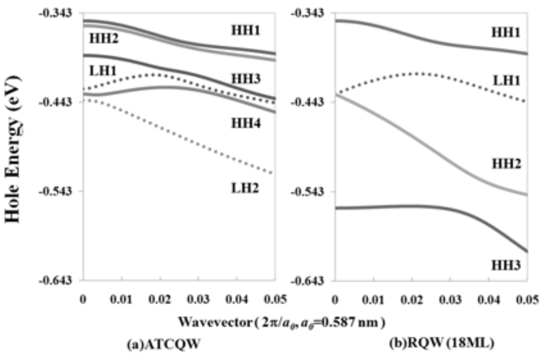

Fig.5 Valence band dispersion (electric field F = 0 kV/cm) for (a) InGaAs/InAlAs ATCQW, and (b) rectangular QW (18ML).

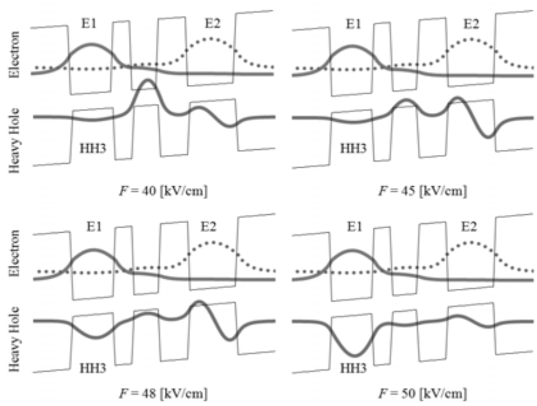

Fig.6 Wavefunction distributions in the InGaAs /InAlAs ATCQW (for wavenumber k = 0.006 x $(2\pi/a_0)$)

$/In_{0.52}Al_{0.48}As$ 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 x $(2\pi/a_0)$ 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 $k\neq0$, causing large positive change in refractive index. The refractive index change $|dn/dF|$ at F =45-50 kV/cm is as large as 1.3×10^{-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.

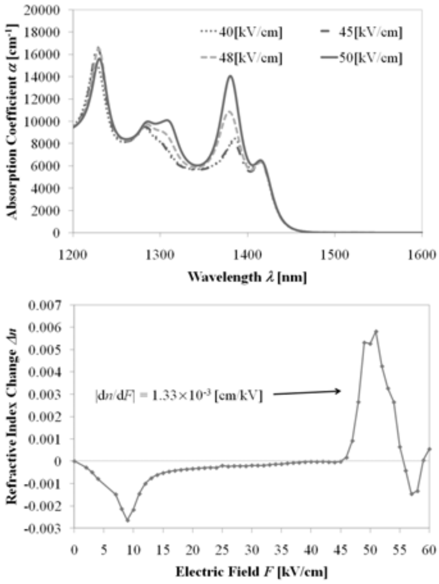

Fig.7 (a) Calculated absorption spectra of InGaAs /InAlAs ATCQW (TE mode). (b) Calculated electrorefractive index change Δn (TE mode) of InGaAs/ InAlAs ATCQW at 1.55μm.

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.

Acknowledgements

This study is partly supported by the Strategic Information and Communications R&D Promotion Program (SCOPE), Ministry of Internal Affairs and Communications, and by a Grant-in-Aid for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] H. Feng, J. P. Pang, M. Sugiyama, K. Tada, and Y. Nakano, IEEE J. Quantum Electron. **34** (1998) 1197.

[2] T. Suzuki, T. Arakawa, K. Tada, Y. Imazato, J.-H. Noh, and N. Haneji, Jpn. J. Appl. Phys. **43** (2004) L1540.

[3] M. Fukuoka, T. Hariki, S. Tajitsu, T. Toya, T. Arakawa, and K. Tada, Euro. Conf. Optical Comm. (ECOC 2008) P.2.22.

[4] W. Endo, T. Arakawa, and K. Tada, Abstr. 69th JSAP Autumn Meeting 2008, 5a-Zn-10 (in Japanese).

[5] S. L. Chuang, Phys. Rev. B. **43** (1991) 9649.