Extended Abstracts of the 2010 International Conference on Solid State Devices and Materials, Tokyo, 2010, pp389-390

Influence of Intrinsic Layer Impurity in InGaAs/InAlAs Asymmetric Triple Coupled Quantum Well on Its Electrorefrative Index Change

Yoshimichi Amma, Kenji Ema, and Taro Arakawa

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

1. Introduction

Semiconductor optical control devices based on phase modulation such as Mach-Zehnder (MZ) modulators and switches are key devices of light fiber communications. For high-performance optical devices based on phase modulation, a large electrorefractive index change Δn with a small absorption loss is necessary in quantum wells. A five-layer asymmetric coupled quantum well (FACQW)[1] is one of the most promising candidates for producing a giant electrorefractive index change. We also proposed an asymmetric triple coupled quantum well (ATCQW)[2]. Operation mechanism of the ATCQW is different from that of the FACQW, and the ATCQW is expected to obtain the electrorefractive index change larger than the FACQW. However, the nonuniformity of an electric field in an intrinsic layer caused by intrinsic impurities may deteriorate its electrorefractive index change.

In this paper, we theoretically discuss the electrorefractive effect in an InGaAs/InAlAs ATCQW for 1.55-μm-wavelength regions and the influence of intrinsic layer impurity on the electrorefractive index change of the ATCQW.

2. Electrorefractive effect in InGaAs/InAlAs ATCQW

Figure 1 shows the structure of the proposed $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ ATCQW structure. The thicknesses of InGaAs well layers are 18(QW1), 10(QW2), 16(QW3) ML, respectively. We call this structure an asymmetric "triple" coupled quantum well. All layers are lattice matched to InP substrate.

Figure 2 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. They were calculated by solving the Schrödinger equations utilizing the $k\cdot p$ perturbation theory with a 4 x 4 Luttinger-Kohn Hamiltonian[3]. When the applied electric field F is changed from -40 kV/cm to -45 kV/cm, the wave function of HH3(the second excited state of heavy hole) moves from QW 2 to QW1 and QW3 ,but the overlap integrals of E1-HH3,E2-HH3 are so small and negligible. As the electric field increases to -50kV/cm, the wave function of HH3 moves to QW1, and the overlap integral of E1-HH3 remarkably increases. As a result, the large absorption is occured. It should be noted that there is no change in the wavefunction distribution for k=0.

The calculated absorption spectra is shown in Figure.3. From -45 to -50 kV/cm, the absorption at around 1380 nm increases because of the transition of E1- HH3 at $k \neq 0$.The dependence of electrorefractive index change Δn on electric

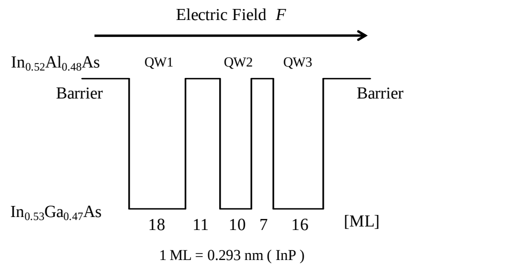

Fig.1 Schematic potential diagram of InGaAs/InAlAs ATCQW.

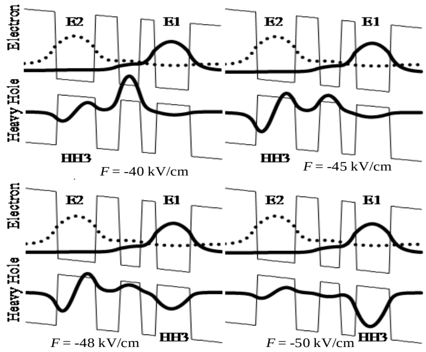

Fig.2 Wavefunction distributions in the InGaAs /InAlAs ATCQW (for wavenumber k = 0.006 x ($2\pi/a_0$)).

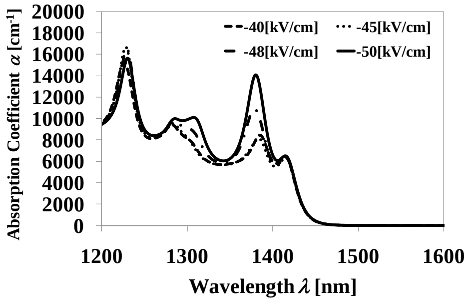

Fig3 Calculated absorption spectra of InGaAs /InAlAs ATCQW (TE mode).

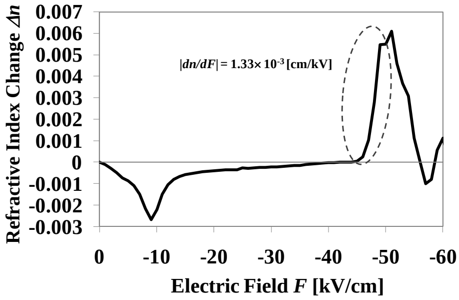

Fig.4 Calculated electrorefractive index change Δn (TE mode) at 1550 nm.

field at 1550 nm wavelength regions is shown in Figure.4. The sensitivity of Δn $|dn/dF|$ at F = –45 ~ –50 kV/cm is 1.3×10^{-3} cm/kV which is three times larger than that of InGaAs/InAlAs FACQW.

3. Influence of intrinsic layer impurity in ATCQW

In Sec. 2, the ideal electrorefractive index change of the ATCQW is discussed. But when we use the ATCQW in practical MZ modulators, we must consider the residual impurity in the intrinsic layer in a p-i-n structures. That is, the space charges of the impurities in a multi ATCQW layer make the electric field nonuniform, and it may deteriorate the electrorefractive index change. Therefore we calculated the influence of the impurity on the characteristic of the ATCQW using the calculation model shown in Fig.5. The 12 sets of the InGaAs/InAlAs ATCQW are used as an intrinsic core layer in a p-i-n junction of a phase modulator. The set numbers are defined as shown in the figure. We assume that the acceptor density N_A, donor density N_D, and impurity density N_i^{-} are 3.0×10^{18} cm^{-3}, 3.0×10^{18} cm^{-3}, and 6.0×10^{15} cm^{-3}, respectively.

First, we calculated the electric field in the core-layer, F_i, under various applied voltages V using the Poisson equation in the p-i-n junction. Secondly, we calculated the electrorefractive index change Δn for each set using F_i under various V and weighted them by the optical power distribution. Figure 6 shows Δn in each set after weighted at 1550nm wavelength regions. It shows the great dependence of the electrorefractive index change on the position. Finally, we calculated phase shift $\Delta\phi$ in an ATCQW phase modulator considering an optical confinement factor and a filling factor of the ATCQW in the core layer. Figure 7 shows the phase shift as functions of an applied voltage. In this figure, the broken line shows ideal case (N_i=0 cm^{-3}) and the solid line is for the case of N_i=6.0×10^{15} cm^{-3}. The result shows that the impurity of the intrinsic layer causes degradation of the phase shift characteristics. This degradation is due to cancellation of positive Δn and negative Δn.

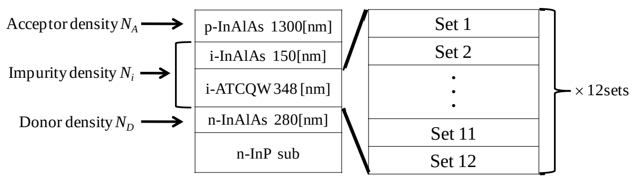

Fig.5 Calculation model for $In_{0.53}Ga_{0.47}As/In_{0.52}Al_{0.48}As$ ATCQW phase modulator.

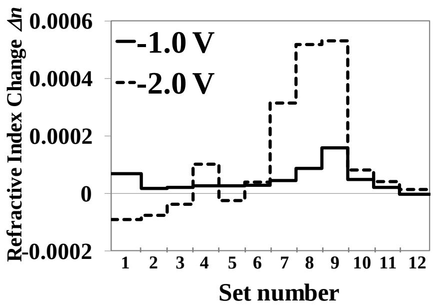

Fig.6 Calculated electrorefractive index change Δn (TE mode) in each set after weighted by optical power distribution.

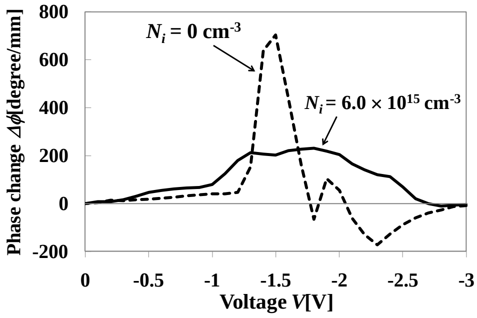

Fig.7 Phase change in an ATCQW phase shifter for various N_i (TE mode) at 1550 nm.

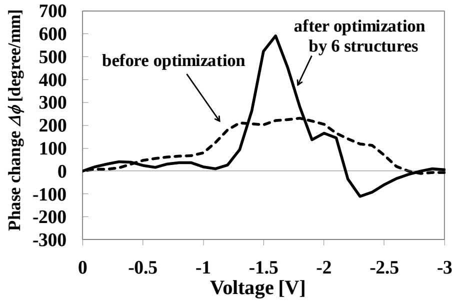

Fig.8 Improvement of phase change characteristics in the ATCQW phase modulator by structure optimization. (N_i=6.0×10^{15} cm^{-3}, TE mode, λ = 1550 nm).

To improve the phase shift characteristics for the case of N_i=6.0×10^{15} cm^{-3}, we optimized the structure of the core layer by changing of the structure of the ATCQW for each set. That is, the structure of the ATCQW is optimized to obtain positive and larger Δn under the electric field at each position. The phase shift of the optimized core layer is shown in Fig.8. The phase shift $\Delta\phi$ is considerably improved. Therefore the ATCQW is very still promising even in practical optical modulators.

4.Conclusion

The electrorefractive effect of an InGaAs/InAlAs ATCQW for 1.55-μm-wavelength regions was discussed. The ATCQW is expected to show giant electrorefractive index change. In addition, the influence of intrinsic layer impurity on its electrorefractive index change was also discussed. The impurity causes degradation of the phase shift characteristic of the ATCQW, but the degradation can be suppressed by optimizing the ATCQW structures.

Acknowledgements

This work is partly supported by SCOPE, Ministry of Internal Affairs and Communications, and Japan Science and Technology (JST), and the Grant-in-Aid for Scientific Research B, Ministry of Education, Culture, Sports, Science and Technology, Japan.

References

[1] M. Fukuoka, T. Hariki, S. Tajitsu, T. Toya, T. Arakawa, and K. Tada, Euro. Conf. Optical Comm. (ECOC 2008) P.2.22.
[2] K.Ema, W.Endo, T.Arakawa, K.Tada, International Conference on Solid State Devices and Materials,(SSDM), Sendai, 2009
[3] S. L. Chuang, Phys. Rev. B. **43** (1991) 9649