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Fabrication and Characterization of InGaAs/InAlAs Multiple FACQW Structures with Larger Tolerance to Impurity in Intrinsic Layer

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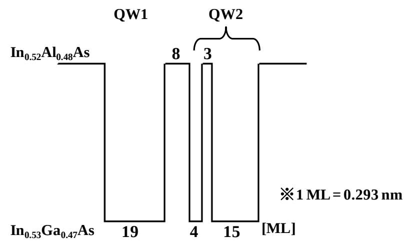
1. Introduction

Semiconductor Mach-Zehnder (MZ) modulators and switches based on phase modulation are key devices of highspeed optical fiber communications. For high -performance semiconductor optical devices based on phase modulation, a large change in electrorefractive index Δn with a small absorption loss is desirable. A five-layer asymmetric coupled quantum well (FACQW)[1,2] is one of the most promising candidates for exhibiting a giant electrorefractive index change by quantum confined Stark effect (QCSE) . However, our previous research indicated that nonuniformity of an electric field in an intrinsic multiple FACQW layer caused by space charges due to residual impurities decreases its electrorefractive index change [3].

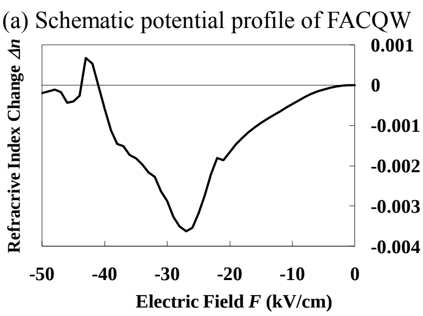
In this paper, we propose and fabricate a multiple FACQW structure to suppress the deterioration in electrorefractive index change, and its optical properties are investigated.

2. Ideal electrorefractive index change in FACQW

Figure 1 (a) shows the previously-proposed structure of InGaAs/InAlAs FACQW for 1.55 μm wavelength region. It is composed of 19 ML quantum well (QW1), 8 ML barrier-layer and 19 ML (4+15) quantum well (QW2). The 3 ML barrier layer in QW2 is inserted for potential modification. This structure is expected to exhibit a large electrorefractive index change by QCSE as shown at a low driving electric field over a wide wavelength range in Fig.1 (b) [2].



(a) Schematic potential profile of FACQW



(b) Calculated electrorefractive index change (TE mode, λ = 1550 nm)

Fig.1. Calculated electrorefractive index change characteristic of ideal InGaAs/InAlAs FACQW.

3. Design of multiple FACQW structure

Figure 2 shows the proposed multiple InGaAs/InAlAs FACQW structure with large tolerance to the nonuniformity of an electric field caused by space charges due to impurities. All layers are lattice-matched to an InP substrate. We assumed the doping densities in p-InP (N_A) and n-InP (N_D) layers are 2.0×10^{18} cm^{-3}. $N_1$and N_2 are the donor ion densities due to oxygen incorporation [4] in Al-free and Al-containing layers, respectively. In this model, $N_1$and N_2 are assumed be 1.0×10^{15} cm^{-3} and 1.0×10^{16} cm^{-3}, respectively. The core layer (i-multiple FACQW) consists of five types of FACQW structures and totally 12 sets of FACQW are used. Each FACQW structure is optimized to exhibit large electrorefractive index change in a different range of an electric field, therefore this multiple FACQW structure is expected to larger tolerance to the nonuniformity of the electric field in the core layer.

Figure 3 shows the calculated phase shift characteristics of the multiple FACQW structures with a pin slab waveguide. The broken line is for multiple FACQW structure

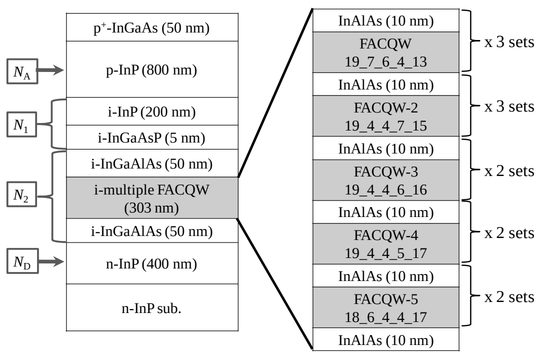


Fig.2 Wafer structure with various types of FACQW structures in the core layer (N_A=N_D=2.0×10^{18} cm^{-3}). The notation "19_8_4_3_15", for example, indicates the FACQW structure shown in Fig.1 (a).

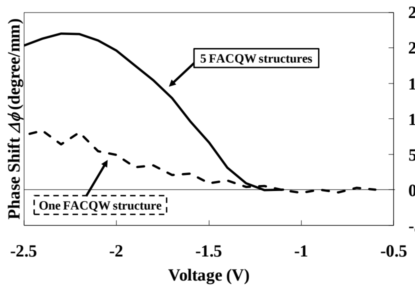


Fig.3 Calculated field-induced phase shift by QCSE in FACQW phase modulator (TE mode, λ = 1550 nm, N_1=1.0×10^{15} cm^{-3}, N_2=1.0×10^{16} cm^{-3}).

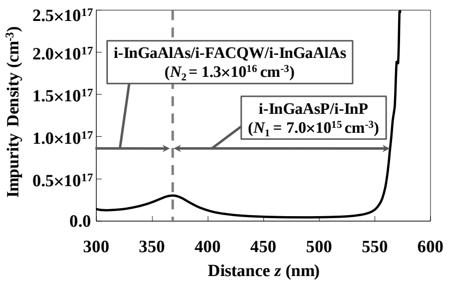


Fig.4. Measured impurity density. Distance z means the distance from the boundary between n-InP and i-InGaAlAs layers.

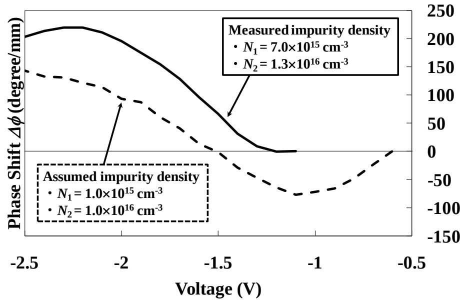


Fig.5 Comparison of the field-induced phase shifts calculated using the assumed and measured impurity density (TE mode, λ = 1550 nm).

with only one type of the FACQW (Fig.1 (a)) in the core layer and the solid line is for that shown in Fig.2. The result shows that the phase shift in the proposed structure with different types of FACQW structure is considerably improved than that in the conventional FACQW structure.

4. Characterization of the fabricated wafer

The wafer with the multiple FACQW structure in Fig. 2 were grown by solid-source molecular beam epitaxy (MBE) and its electrical and optical characterics were measured. Figure 4 shows the space charge densities measured by capacitance-voltage (C-V) method. The space charge densities N_1 and N_2 were evaluated to be 7.0×10^{15} cm^{-3} and 1.3×10^{16} cm^{-3}, respectively. The phase shift characteristics recalculated using these measured density are shown in Fig.5. The calculated field-induced phase shift is comparable to that calculated using $N_1=1.0\times10^{15}$ cm^{-3} and $N_2=1.0\times10^{16}$ cm^{-3}. This results indicates the proposed structure using multiple FACQW structures still has large tolerance to the nonuniformity of the electric field.

Figure 6 shows the absorption spectra calculated using the measured space charge densities. With the increase of a reverse voltage from 1.1 V to 2.0 V, the absorption peak at around 1440 nm increases, and this change in absorption leads to the phase shift in Fig. 5. The spectra were calculated by summing the absorption spectra weighted with the confinement factor in each FACQW layer.

Figure 7 shows the measured photocurrent spectra of the fabricated wafer under various voltages. Compared to Fig. 6, the change in photocurrent peak at around 1440 nm in Fig. 7 is similar to that in Fig. 6. This result shows a phase modulator using this wafer is expected to exhibit large phase shift at a low driving voltage. On the other hand, the absorption peaks at around 1380nm, 1390 nm, and 1460 nm were observed as shown in Fig. 7. These peaks do not appear in Fig. 6. The reason for this discrepancy is that the grown structure is slightly different from the designed.

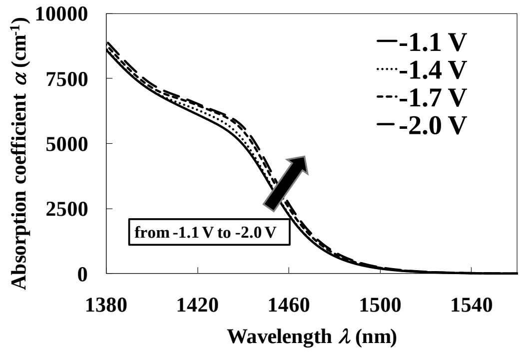


Fig.6 Calculated absorption coefficient spectra of the wafer (TE mode, $N_1=7.0\times10^{15}$ cm^{-3}, $N_2=1.3\times10^{16}$ cm^{-3}).

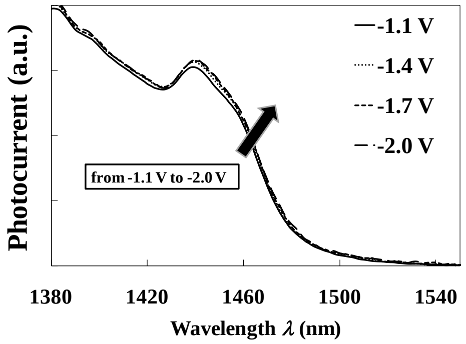


Fig.7 Measured photocurrent of the wafer under various bias voltages (TE mode).

5. Conclusion

The fabrication and characterization of the wafer using multiple FACQW structures in the core layer were discussed. The theoretical analysis shows that the proposed multiple FACQW with five types of structure is expected to exhibit large field-induce phase shift even in a nonuniform electric field caused by the space charges due to residual impurities. The proposed structure was grown by MBE and its electrical and optical characteristics were measured. The measured photocurrent spectra were consistent with the theory. Highspeed and low-voltage MZ modulators and switches are expected to be realized using the proposed FACQW structures.

Acknowledgements

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