13D1-4

The Impact of InAlGaAs Barriers on Material and Differential Gain of Quantum Wells on Low Indium Content InGaAs Ternary Substrates

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Abstract: The impact of InAlGaAs barriers on material and differential gain of quantum wells (QWs) on InGaAs substrates is theoretically investigated. Material gain of QWs with InAlGaAs barriers can be largely increased because of deeper ΔE_c.

1. Introduction

1.3-μm lasers for data communications systems operating in a wide temperature range are strongly desired. Quantum Well (QW) lasers grown on InGaAs ternary substrates are promising candidates for high-temperature operation because of their large conduction band offset ΔE_c [1]. Lasers fabricated on InGaAs substrates with relatively large In content exhibit excellent temperature characteristics [2]. But the results were limited to substrate with In content of 0.2 to 0.3 because a highly strained well layer is required in order for low-In-content substrate to obtain 1.3-μm light. However, deeper ΔE_c can be available and the fabrication of substrates is easier for low-In-content substrates. Recently, lasers on low-In-content (In:0.1) InGaAs substrate have been realized [3]. In [3], an InGaAs was used for the barrier layer. By introducing an InAlGaAs barrier, gain and temperature characteristics can be improved further due to the large barrier height of InAlGaAs compared with that of InGaAs barrier. Furthermore, although the In content of the substrate is an important design parameter for QWs on InGaAs substrates, the influence of the In content of the substrate has not been discussed theoretically. Therefore, it is important to investigate the performance of QWs on ternary substrate for various materials and structural parameters.

In this paper, the material gain and differential gain of InGaAs/InAlGaAs QWs on InGaAs ternary substrates are theoretically investigated. It is shown that the material gain of InGaAs/InAlGaAs QWs becomes 30% larger than that of InGaAs/InGaAs QWs and the temperature dependency is largely improved.

2. QW Structures and Analysis Methods

The left side of Fig. 1 is a schematic of the QW structure we analyzed. The structure consists of three QWs with 120-nm SCH layers and InGaP cladding layers. The thicknesses of the well and barrier layers are 10 and 20 nm, respectively. The well layer is InGaAs and barrier and SCH layers are InGaAs or InAlGaAs. The strain of the well layer was adjusted to obtain 1.3-μm band-gap between the first conduction and valence sub-bands.

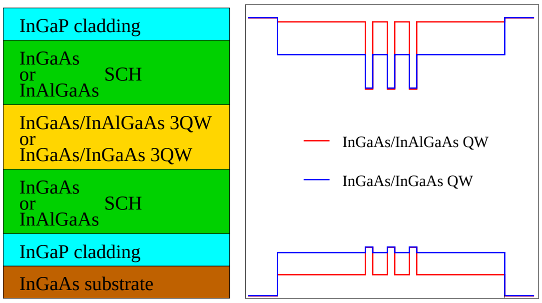

Fig. 1. Schematics of the QW structure and potential profile.

Band lineups were obtained using the tight-binding approach, taking into account of repulsion from a cation d-orbital [4], and a flat band was assumed because of the deep ΔE_c. The valence band energy dispersion relation was calculated using the block diagonalized 6×6 Luttinger-Kohn Hamiltonian to include the effect of spin-orbit split-off bands [5] while parabolic bands were assumed for conduction bands. The band structure of the QWs was calculated for given barrier and SCH materials and substrate In content by solving the effective-mass equation discretized by finite-element method. Material parameters used in the simulation were extracted from [6]. Based on the calculated band structure, the quasi-Fermi level, material gain, and differential gain were obtained for given carrier density and temperature. Lorentzian broadening of energy spectrum was assumed in calculating material gain.

3. Results for Material Gain, Differential Gain, and Temperature Dependency

The right side of Fig. 1 shows the potential profiles of the QWs on $In_{0.15}Ga_{0.85}As$ substrates. For the InAlGaAs barrier, the band-gap wavelength is 0.8 μm (Al:0.26). Compressive strain of 2.35% is assumed in the well layer. By using InAlGaAs barriers, ΔE_c almost doubles (410 meV) compared with that of InGaAs barriers (210 meV).

Fig. 2 shows the peak material gain as a function of carrier density. We can see that the material gain of InGaAs/InAlGaAs QWs is 30% larger than that of InGaAs/InGaAs QWs. This is because the deeper ΔE_c prevents electrons from filling higher energy sub-bands. For high temperatures, the material gain of the QWs is reduced because the quasi-Fermi level becomes smaller due to the large density of states in higher energy states. When the temperature is increased, the degradation of material gain for the InGaAs/InAlGaAs QWs is smaller than that of the InGaAs/InGaAs QWs, indicating the superiority of InAlGaAs barriers for high-temperature operation. Fig. 3 shows the differential gain as a function of carrier density. At room and high temperature near the threshold, differential gain of the InGaAs/InAlGaAs QWs is 20% larger than that of the InGaAs/InGaAs QWs, showing the possibility of high-speed operation in the high temperature environment.

One of the interesting features of QWs on ternary substrates is the flexibility of the substrate composition. By changing the In content of the substrate, various characteristics of QWs can be largely tuned. Fig. 4 shows the carrier density for obtaining material gain of 1000 cm^{-1} as a function of temperature for various In contents of the substrate. Compressive strains of 2.8 and 1.9% in the well layer were assumed for $In_{0.1}Ga_{0.9}As$ and $In_{0.2}Ga_{0.8}As$ substrates. Barrier band-gap wavelengths are assumed to be 0.76 (Al:0.26) and 0.84 μm (Al:0.25) for $In_{0.1}Ga_{0.9}As$ and $In_{0.2}Ga_{0.8}As$ substrates. The slope of carrier density to temperature of the InGaAs/InGaAs QWs is larger than that of the InGaAs/InAlGaAs QWs as discussed above. This feature is more evident for QWs on high In content substrate. For $In_{0.2}Ga_{0.8}As$ substrate, the carrier density to obtain 1000 cm^{-1} material gain is increased 25%, while the increase is 16% for $In_{0.1}Ga_{0.9}As$ substrate. This is because, for low In content substrate, electrons are strongly confined in the well region even in the high-temperature environment due to the larger values of ΔE_c.

4. Conclusion

We have theoretically clarified the material gain, the differential gain, and the temperature dependency of QWs on InGaAs ternary substrates can be greatly improved by using InAlGaAs barriers and low In content substrates. The material gain of InGaAs/InAlGaAs QWs is 30% larger than that of InGaAs/InGaAs QWs.

References

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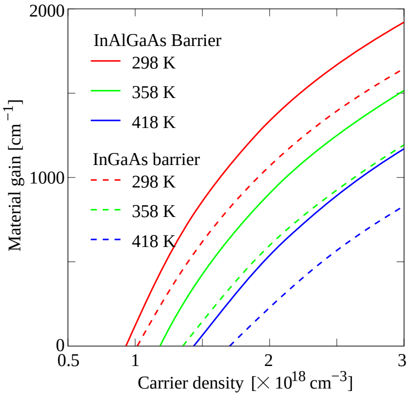

Fig. 2. Peak material gain as a function of carrier density.

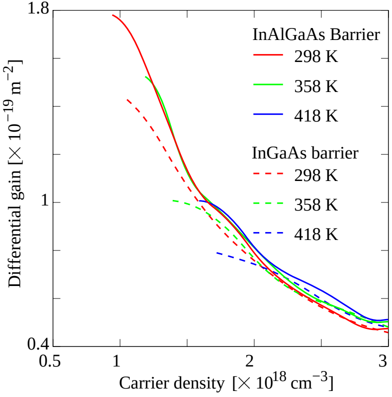

Fig. 3. Differential gain as a function of carrier density.

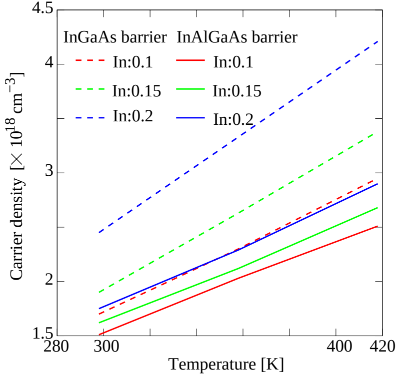

Fig. 4. Carrier densities for obtaining material gain of 1000 cm^{-1} as a function of temperature.