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Structure Design and Analysis of 2 μm InGaAsSb/AlGaAsSb Multi-Quantum Well Laser Diode with Carrier Blocking Layer

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Received: 22 November 2018; Accepted: 30 December 2018; Published: 4 January 2019

Abstract: A low threshold current density of 2 μm InGaAsSb/AlGaAsSb multi-quantum well (MQW) laser diode with carrier blocking layer (CBL) is demonstrated by simulation and fabrication. The carrier leakage is found to be theoretically suppressed for the devices with CBL. All the laser wafers are grown with a solid source Molecular Beam Epitaxy (MBE) System. Experimental results reveal the samples with CBL exhibits ultra-low threshold current densities of 142 A/cm² and high slope efficiency of 0.158 W/A, which is better than 215 A/cm² and 0.122 W/A achieved in the conventional InGaAsSb/AlGaAsSb LDs at room temperature. This improvement in device performance comes from meticulously designing the carrier blocking layers to increase carrier confinement and injection efficiency.

Keywords: 2 μm laser diode; InGaAsSb/AlGaAsSb; quantum-well; carrier leakage

1. Introduction

InGaAsSb/AlGaAsSb quaternary quantum well systems have recently become increasingly prominent due to their potential application as semiconductor diode lasers emitting at wavelengths of around 2 μm , which are in high demand for a variety of applications, including fire detection, infrared imaging sensors, molecular spectroscopy and low loss optical fiber communications [1–4]. However, the high threshold current density, strongly temperature sensitive 2 μm InGaAsSb/AlGaAsSb LDs caused by Auger recombination rates at the MQW active region and large carrier leakage losses in cladding layers remain a great challenge [5,6]. In order to solve this problem, more attention is now focused on the improvement of molecular beam epitaxy (MBE) fabrication technology of antimonide LDs, but the reports about optimization for the structure of 2 μm InGaAsSb/AlGaAsSb LDs are rare. It is reported that a proper increase of the quantum well number in the active region is an effective solution to solve the above problems, but a high number can degrade the output characteristics of LDs [7,8].

Based on band engineering and carrier transportation mechanisms [9,10], 2 μm InGaAsSb/AlGaAsSb multi-quantum well laser diode with carrier blocking layer (CBL) is proposed, with the aim of reducing the threshold current density and improving injection efficiency.

2. Theoretical Analysis

In order to understand the carrier dynamics inside the active region of LDs, the carrier transportation mechanisms are investigated. Figure 1 illustrates the carrier transport process in the InGaAsSb/AlGaAsSb 3QWs LD.

Figure 1. Schematic diagram of carrier leakage of InGaAsSb/AlGaAsSb 3QW LD.

As shown in Figure 1, the electrons injected from the N-side into the active region are captured by the first quantum well, and are transferred to the next quantum well by tunneling or diffusing the barrier. The process is repeated until the electrons flow into the P-side. The energy discontinuity between the waveguide and cladding layers could prevent the minority carriers from following into the high-doped area. But for antimonide materials, the small conduction band offsets reduce the carrier confinement, and the high mobility of carrier electrons further accelerate the minority carriers spilling over the active region. The minority carrier concentration N_1 is calculated by using the following equation [10]:

$$N_1 = \frac{1}{2\pi^2} \left(\frac{2m}{\hbar^2} \right)^{\frac{3}{2}} \int_{\Delta E_c}^{\infty} \frac{(E - E_c) dE}{1 + \exp\left(\frac{E - F_n}{kT}\right)} \quad (1)$$

where $\hbar = \frac{h}{2\pi}$, h is Planck constant, m is electron effective mass, F_n is the Fermi level, and k is the Boltzmann's constant. Equation (1) indicates that the concentration of minority carriers decreases with increase of the conduction band offset ΔE_c .

The electron leakage current density J_1 can be estimated by using the following formula, if only considering the thermionic emission diffusion:

$$J_1 = e \frac{D}{L} N_1 \quad (2)$$

where D and L are the electron diffusion coefficient and length at the P-side respectively. When the carriers are injected into the active region, they can either recombine radiatively or not radiatively. The lowest threshold current density J_2 is modeled as Equation (3).

$$J_2 = e \frac{d}{\tau} N_{th} \quad (3)$$

where τ is the electron average lifetime and d is the thickness of the active region. Thus, the laser threshold current density J_{th} is calculated as follows:

$$J_{th} = J_1 + J_2 = e \frac{D}{L} N_1 + e \frac{d}{\tau} N_{th} \quad (4)$$

From Equation (4), it is known that the laser threshold current density can be reduced with the decrease of carrier leakage. Therefore, a large band offset between the waveguide and cladding layers should be designed elaborately to block the minority carriers from flowing into the high-doped area in order to improve the opto-electrical properties of 2 μm InGaAsSb/AlGaAsSb LDs.

N-side, the ΔE_v for minority holes is slightly increased from 0.953 eV to 1.024 eV, which leads to the concentration of holes leakage being reduced from 10^2 cm^{-3} to $10^{1.5} \text{ cm}^{-3}$.

Table 1. Key parameters of related binary compounds in antimonide material database.

	GaAs	InAs	AlAs	GaSb	AlSb	InSb
a0 (Å)	5.6523	6.0584	5.6605	6.0959	6.136	6.479
dielectric-constant	13.1	15.15	10.1	14.8	10.3	16.8
electron-mass	0.067	0.026	0.15	0.039	0.14	0.0135
affinity	4.07	4.07	3.5	4.06	3.65	4.59
c11	11.9	8.33	12.02	8.842	8.769	6.487
c12	5.38	4.53	5.7	4.026	4.341	3.735
Eg (eV)	1.424	0.3595	3	0.725	2.3	0.1737
real-index	3.65	3.892	3.006	3.9731	3.29	4
electron-mobility	0.85	1	0.02	0.22	0.02	5
hole-mobility	0.004	0.036	0.279	0.1	0.04	0.07
thermal-kappa	55	2.7		32		18

Figure 3. band diagrams and carrier concentrations distributions in the various InGaAsSb/AlGaAsSb 3QW LDs at 400 mA (a) Without CBL (b) With CBL. The grey shadow indicates the bandgap and the blue shadow indicates the location of the carrier blocking layer.

Figure 4 plots the simulated radiative recombination rates in the active region of the two various structures. It is obviously seen that the radiative recombination rates in the last quantum well are the highest ones. This can be attributed to the highest carrier concentration accumulated in the last QWs next to the *p*-type layer. The higher radiative recombination rates in the active region are also observed for the devices with CBL, which proved that the CBL can result in a reduction of the carrier leakage and enhancement of the carriers injection in the active region.

The simulated P-I (optical power-current) characteristics for the 0.8-mm-long devices with and without CBL having the stripe width of 90 μm resonator length are illustrated in Figure 5. It can be found that the threshold current density is reduced from 197 A/cm² to 126 A/cm² and the differential efficiency (η_d) is increased from 0.154 W/A to 0.193 W/A due to the optimization of the epitaxial structure design.

Figure 4. Radiative recombination rate of various InGaAsSb/AlGaAsSb 3QWS LDs at 400 mA.

Figure 5. Simulated P-I characteristics of various InGaAsSb/AlGaAsSb 3QW LDs.

Furthermore, in order to predict the beam quality of the new-proposed laser diode, the far-field radiation profiles are also simulated. The vertical divergence angles are only 40° as shown in Figure 6, which is better than most of these devices.

Figure 6. Simulated vertical angle divergence of 2 μm InGaAsSb/AlGaAsSb LDs with CBL.

Based on our previous experience and research for this work [11,12], the 2 μm InGaAsSb/AlGaAsSb samples without and with CBL are fabricated by using solid source molecular beam epitaxy (MBE) technology to further test these predictions. After growth, the Ti/Pt/Au is deposited as the P-electrode, the wafer is thinned to about 90 μm in thickness, and then deposited with AuGeNi/Au bottom contact and alloyed. All the wafer is cleaved into Fabry-Perot laser chips with cavity length of 800 μm by conventional steps. The structures are mounted epi-side down onto copper heat sinks, and the facets are kept uncoated.

The CW output power and operation voltage characteristics versus current of the various devices are illustrated in Figure 7. It can be seen that the optimized 2 μm InGaAsSb/AlGaAsSb LD with CBL exhibited the threshold current density is as low as 142 A/cm² and η_d is 0.158 W/A, while for the conventional devices, the threshold current density of the fabricated is 215 A/cm² and η_d is 0.122 W/A. The experimental results are basically in agreement with the theoretical results, the small difference comes from the unavoidable technological and processing error.

Figure 7. CW output power characteristics measured at 300 K for the various InGaAsSb/AlGaAsSb LDs with 90 μm stripe width (a) Without CBL (b) With CBL.

5. Conclusions

In summary, we have demonstrated a 2 μm InGaAsSb/AlGaAsSb laser diode with a graded composition AlGaAsSb carrier blocking layer (CBL) emitting at 2 μm by simulation and fabrication. The material database of InGaAsSb/AlGaAsSb LDs is set up to predict the optical and electrical properties of devices. The simulation results indicate that the graded interlayer can reduce the concentration of electrons leakage from 10^7 cm^{-3} to near 0, which results in a significant improvement in the radiative recombination rate and leads to a reduction of threshold current density compared to the conventional LDs. All the laser wafers are grown by using a solid source MBE system. The threshold density and slope efficiency of the optimized InGaAsSb/AlGaAsSb LD with CBL is 142 A/cm² and 0.158 W/A, which is better than 215 A/cm² and 0.122 W/A achieved in un-optimized devices at room temperature. This effect is attributed to an improved carrier injection and confinement that prevents carrier leakage into the high-doped region of the LDs while simultaneously enhancing carrier injection into the active region.

Author Contributions: Conceptualization, Ning An and Lei Ma; methodology, Ning An and Guanyu Wen; software, Zhipeng Liang and Haitao Zhang; validation, Tianshu Gao, Haitao Zhang and Lei Ma; formal analysis, Ning An; investigation, Ning An; resources, Haitao Zhang and Cunbo Fan; data curation, Haitao Zhang and Cunbo Fan; writing—original draft preparation, Ning An; writing—review and editing, Ning An; visualization, Zhipeng Liang; supervision, Cunbo Fan; project administration, Ning An; funding acquisition, Ning An.

Funding: This research was funded by Excellent Youth Foundation of Jilin Province Scientific committee: 20170520155JH, National Natural Science Foundation of China: 61605220.

Acknowledgments: The content is supported by Key Laboratory of Space Object and Debris Observation, Purple Mountain Observatory, Chinese Academy of Science.

Conflicts of Interest: The authors declare no conflict of interest.

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