Research Article

2.3 μm InGaAsSb/AlGaAsSb Quantum-Well Laser Diode via InAs/GaSb Superlattice Layer on GaAs Substrate

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We present 2.3 μm InGaAsSb/AlGaAsSb type I laser diodes (LDs) on GaAs substrate; a superlattice (SL) layer was introduced as an interconnecting layer playing an important role in manipulating the optical field distribution and reducing free-carrier absorption in multiquantum wells (MQWs) for achieving balanced and optimal LDs performance. Accordingly, power of 8.6 mW was obtained with 2.3 μm wavelength. Our results demonstrate that superlattice layer may open a new avenue for high performance and improvement in mid-infrared laser diode.

1. Introduction

Laser diodes being emitted located in mid-infrared wavelength range have become one of the international frontier areas. These devices are especially attractive and have enormous interest for the development of the practical realization of optoelectronic devices operating in the wavelength range, with potential applications in a wide variety of areas including communications, altimetry, ranging, optical sensing, and monitoring. For these applications, low cost, high performance diode lasers operating in the continuous wave (CW) region at room temperature (RT) are required [1].

In spite of having excellent characteristics in the 2 to 3 μm range, GaInAsSb/AlGaInAsSb QW laser diodes in recent years have allowed obtaining continuous wave and RT operation in the wavelength region extending from 2.0 to 3.4 μm [2–6]. A series of Sb-based semiconductor laser device results, with improved output performance and excellent temperature characteristics, have been obtained owing to the laser structure design, materials optimization, and epitaxial growth. Laser diodes based on compressively strained quaternary type I structure, operating within the 2 to 3 μm spectra region, can provide optical powers up to the watt level in CW mode at room temperature. Integration of those lasers on a Si or GaAs platform could allow a more cost-efficient production together with the emergence of unique

functionalities if it can be coupled with a complementary metal-oxide semiconductor circuitry [7–9].

However, the GaSb substrates have a strong absorption in the interest IR wavelength region due to free-carrier absorption, and it is very difficult to eliminate the free-carrier absorption [10–13]. Additionally, GaSb substrates based devices are hard to integrate with read-out circuits in a monolithic technology. Thus for commercial and technical motivations, growth of devices on GaAs substrates is encouraged. To overcome the problem of large lattice mismatch ($\sim 7.8\%$) between GaSb and GaAs, which can lead to large amount of dislocations, SL layers have been utilized [3].

In this paper, we investigated the optimized growth conditions, laser structures design, and doping characters of InGaAsSb/AlGaAsSb MQW lasers, which were grown with superlattice layer, and GaSb-based type I diode lasers with up to 2.3 μm wavelength was fabricated and characterized, indicating excellent lattice matching and thus high crystalline quality.

2. Experiment

The device was grown by molecular beam epitaxy using a reactor equipped with tellurium and beryllium dopant cells and arsenic/antimony valved cracker cells. Before loading in

FIGURE 1: Schematic device of InGaAsSb/AlGaAsSb quantum-wells laser diode with superlattice layer.

the MBE growth chamber, the substrate was outgassed for several hours at 200°C. The substrate was then heated to 580°C for 30 min to remove residual oxide and finally cooled down to 560°C for the epitaxy device.

A schematic of the LD structure was shown in Figure 1. The GaAs buffer layer was grown at 500°C about 80 nm and the SL layer structure of 9 periods of InAs/GaSb superlattice layer grown at 410°C; the thickness of one period was about 60–70 nm. As was measured by the reflection high-energy electron diffraction (RHEED) pattern. Strain balancing was accomplished by encouraging In/Sb like interfaces, with migration enhanced epitaxy used on the normal (InAs on GaSb) interface and Sb soaking on the inverted interface [14, 15]. One monolayer of In was deposited in the interface formed, followed by a short growth interrupt, Sb was soaked to help form the InSb layer, and As was soaked to remove excess Sb on the growth surface. As the growth continued, a reduction in the specular spot size was observed, indicating a smoothing of the sample surface achieved with layer by layer growth.

The laser structures were grown on InAs/GaSb SL layer; the thickness of the period is about 60–70 nm. Heavily doping sources with Be and Te to a concentration of $2.0 \times 10^{18} \text{ cm}^{-3}$ and $1.0 \times 10^{18} \text{ cm}^{-3}$, respectively were obtained. The active region consists of three 10 nm thickness $\text{In}_{0.36}\text{Ga}_{0.64}\text{As}_{0.03}\text{Sb}_{0.97}$ quantum wells surrounded by $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.02}\text{Sb}_{0.98}$ barriers, and 1.4% compressively strain existed in the quantum wells; 300 nm undoped $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.02}\text{Sb}_{0.98}$ lower waveguide layer and 300 nm $\text{Al}_{0.35}\text{Ga}_{0.65}\text{As}_{0.02}\text{Sb}_{0.98}$ upper waveguide layer were sequentially grown. High Al contributes to an improved resistance and injection efficiency, while adding Al composition of >0.35 can increase the valence band offset for better hole confinement. 1 μm thick Te-doped $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}_{0.07}\text{Sb}_{0.93}$ lower cladding layers and 1 μm thick Be-doped $\text{Al}_{0.9}\text{Ga}_{0.1}\text{As}_{0.07}\text{Sb}_{0.93}$ upper cladding layer were grown. The high Al content >0.9 was necessary to heavily

n-type dope the cladding layer with Te and the lower refractive index for sufficient gain overlap. The Be-doped [$1.0 \times 10^{19} \text{ cm}^{-3}$] Ohmic contact layers were grown.

We used a standardized processing procedure to produce samples for characterization. The InGaAsSb/AlGaAsSb laser structure with stripe width of 50 μm and cavity length of 1000 μm was fabricated, and contacts were defined using standard photolithography. The n-side of the wafer was thinned to a thickness of about 130 μm by mechanical method. Conventional Ti-Pt-Au and Au-Ge-Ni contacts were evaporated as the top p- and n-contacts, respectively. After alloying, the laser facets were coated with antireflection (AR) and high reflection (HR) thin films, with reflection of 5% and 95%, reflectivity, respectively. The lasers were soldered on copper heat-sinks for heat dissipation.

3. Results and Discussion

The previous studies indicate that, at the initial stages of deposition of GaSb epilayers on GaAs substrates, three-dimensional GaSb islands nucleate sparsely on the substrate surface. Continued deposition leads to elongated GaSb islands, which eventually coalesce together and form a planar film. The resulting epilayers exhibit a high defect density and severe multiple twinning.

Therefore, in this work, we have also observed that introducing a InAs/GaSb superlattice layer similar as buffer layer can improve the quality of InGaAsSb/AlGaAsSb MQWs and demonstrated that the InAs/GaSb superlattice interlayer and the role of a surfactant on GaAs substrates could improve the crystal quality of GaSb-based films, because of further the lowest interface energy.

The cross-section images of superlattice interlayer were characterized by scanning electron microscopy (SEM) and displayed in Figure 2. The images clearly reveal that the superlattice layers successfully exhibit rather smooth; the well-defined morphologies can be attributed to two reasons: one has been confirmed that the InAs/GaSb superlattice interlayer also effectively relaxes the mismatch strain by forming misfit dislocations localized at the interface and enhances the quality of subsequent AlGaAsSb cladding layers growth and the other is the significant improvement in quality of various group III Sb-based compounds grown on GaAs substrates attributing to InAs/GaSb islands acting as appropriate nucleation sites for AlGaAsSb due to decreased interfacial surface energy as well as significantly smaller misfit strain of 0.6% with superlattice layer.

The output power versus current (L-I) characteristic under CW operation at the room temperature in Figure 3 reveals a threshold current of about 220 mA/cm². The output power measured in CW operation over the temperature between 20°C and 50°C. The maximum output power is 8.6 mW at a drive current about 240 mA at 20°C

The low threshold is attributed to the excellent crystalline quality and reduced the optical absorption of the injected free carriers in the QW layers. It is inferred from the experimental results that using the superlattice buffer will be beneficial for reducing the optical absorption of the injected free carriers

FIGURE 2: SEM image of the superlattice layer.

FIGURE 3: Output characteristics of 2.3 μm laser diode under CW operation.

FIGURE 4: Laser spectrum of the InGaAsSb/AlGaAsSb quantum-wells laser diode at room temperature under the current of 150 mA, 180 mA, and 200 mA.

in the QWs layers. This is because such a structure allows the optical loss in the waveguide to be minimized, increasing the optical field reflection into the p-cladding layer with the superlattice basing the role of a reflective mirror, so the optical mode distributions are shifted away from the center of the waveguide towards the n-cladding layer [15]. This will lead to lower free-carrier absorption and the optical loss in the waveguide to be minimized, improving the differential quantum efficiency and power output.

In addition, lattice-matched barrier and the superlattice provide good confinement for both electrons and holes at a lower bandgap difference between the barrier and the QW. The latter effect reduces the quantum defect and subsequent heat generation in the active area.

Figure 4 shows the lasing emission spectra of the laser diode measured under CW operation at room temperature with the current of 150 mA, 180 mA, and 200 mA,

which consist of multiple longitudinal modes. Laser central peak emission wavelength is around 2307 nm for 150 mA, 2308.1 nm for 180 mA, and 2308.5 nm for 200 mA at room temperature, respectively.

4. Conclusions

In conclusion, the InGaAsSb/AlGaAsSb quantum-wells laser diode with the superlattice interlayer was demonstrated. Through growth 9 pairs of superlattice interlayer on the GaAs substrate, the optical loss and carrier at the active region were significantly reduced. Moreover, the optical field distribution in MQWs could also be modulated by this superlattice to result in much balanced carriers. Finally, power up to 8.6 mW was demonstrated. This study establishes a new feasible device architecture for future development of high performance and efficient laser diode.

Competing Interests

The authors declare no competing interests.

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