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Multi-Staged, InAsSb Mid-Infrared Lasers and Light-Emitting Diodes, Grown by MOCVD

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Due to lower nonradiative rates, mid-infrared (2-6 micron) lasers with strained, narrow bandgap, Sb-based active regions have the potential to operate at lower current density and higher temperature than competing devices. Superior performance may be achieved through the "band structure engineered" reduction of Auger recombination and the implementation of multi-stage (or "cascaded") active regions. We describe the first lasers and LEDs utilizing strained InAsSb, multi-stage active regions. An (n)InAs / (p)GaAsSb semimetal layer is incorporated into each stage as an internal electron-hole source. To date, 2-stage LEDs and 2-stage lasers have been demonstrated. Our multi-stage devices were grown by MOCVD.

Introduction

Chemical sensor and infrared countermeasure technologies would become viable with the availability of high power, mid-infrared (3-6 μm) lasers and LEDs operating near room temperature. However, the performance of mid-infrared emitters has been limited by nonradiative recombination processes (usually Auger recombination), which dominate radiative recombination in narrow bandgap semiconductors. Potentially, Auger recombination can be suppressed in "band-structure engineered", strained Sb-based heterostructures. Along with material development efforts, we are exploring novel multi-stage (or "cascaded") active regions to improve the performance of Sb-based, mid-infrared lasers and LEDs. In this paper, we present a "progress report" on novel InAsSb-based, mid-infrared devices grown by metal-organic chemical vapor deposition (MOCVD), and compare these results with molecular-beam epitaxy-grown, InAs/GaInSb type II superlattice devices.

The injection devices described in this work contain a GaAsSb (p) / InAs (n) heterojunction to form an internal, semi-metal layer.[1,2] In these devices, the semi-metal acts as an internal electron source which can eliminate problems associated with electron injection (specifically electron blocking by cladding conduction band offsets, n-type doping of claddings, and excess heating due to thermalization of hot carriers), and this design is compatible with MOCVD materials and background doping. Furthermore, the use of an internal electron-hole source enables us to consider alternative laser and LED designs that would not be feasible with conventional, bipolar devices. Using the semi-metal, InAsSb-based multi-staged active regions can be constructed (see Figure 1a) where in the absence of non-radiative losses, several photons would be generated for every carrier injected at the device contacts. A two stage LED and a 2-stage laser are described in this work to demonstrate the feasibility of our idea. Similar to the multi-staged InAsSb devices, we have reported cascaded, type II InAs/GaInSb LEDs and lasers.[3,4] (see Figure 1b) Competing with the Sb-based mid-infrared devices, unipolar quantum cascade lasers have received much acclaim.[5] However, the nonradiative (optical phonon) lifetimes of the unipolar devices are orders of magnitude shorter than the Auger-limited lifetimes for interband devices, and with multi-staging, mid-infrared interband Sb-based lasers should have lower threshold currents than unipolar quantum cascade lasers.

Multi-Staged (Cascaded) Device Demonstrations

As an initial demonstration of a multi-staged bipolar device, we produced a 2-stage/ 2-color LED using InAsSb quantum wells with 11% Sb in one stage and 13% Sb in the other.[1] Each stage is the segment A-B in Figure 1a. In each stage, pseudomorphic InAsSb quantum wells are separated by 500 Å

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(a) Multi-stage, Strained InAsSb Active Region -

(b) Cascaded, Type II InAs/GaInSb Active Region -

Figure 1 - (a) Diagram of a multi-stage laser active region with compressed, type I InAsSb quantum wells, semimetal electron injection, and AlAsSb electron block.[1] (b) Diagram of a cascaded laser active region with a type II, InAs/GaInSb lasing transition. Electron-hole (e-h) pairs are generated at the AlSb, e-h tunnel barrier in each stage.[2,3]

Figure 2 - Emission and photoluminescence spectra of a 2-stage, 2-color LED with InAsSb MQW active regions with 11% and 13% Sb respectively. Emission from a 1-stage LED, with 11% Sb, is also shown.

Figure 3 - Emission spectrum of a 2-stage semimetal injection laser with 5 InAsSb QWs in each stage.

of InAs. (The InAsSb devices are grown on n-type, InAs substrates.) A 600Å thick $\text{AlAs}_{0.16}\text{Sb}_{0.84}$ electron barrier is placed between the 2 stages. Low temperature emission spectra from the 2-stage LED showed two peaks, corresponding to emission from each stage for the 2-stage device. Emission from a 1-stage LED (grown during the same run and removed from the growth chamber in the middle of the run) which clearly corresponds to 1 peak of the 2-stage emission is also shown. (see Figure 2) The relative intensities of the peaks of the 2-stage device are comparable to those observed in PL, which indicates that electrons are independently generated in each stage.

Multi-stage injection laser emission at 3.8 μm is shown in Figure 3. Similar to the previous LED, the laser active region consisted of 2 stages, each containing 5 pseudomorphic InAsSb quantum wells. Between stages, 200 Å of $\text{AlAs}_{0.16}\text{Sb}_{0.84}$ and 300 Å of compositionally graded AlGaAsSb are used to confine electrons in the active region and to prevent the build-up of holes in the GaAsSb layer. The top and bottom claddings were 2 μm of $\text{AlAs}_{0.16}\text{Sb}_{0.84}$. The overall material quality for this laser was poor. Compositional drift during growth caused lattice mismatch, and 2-color lasing may be occurring in Fig. 3 due to differing Sb composition of the InAsSb quantum wells of the 2 stages. Gain guided stripe lasers, 1 mm long were fabricated, and the lasers were tested under pulsed conditions. The threshold current density at 80K was 3.2 kA/cm², and the maximum operating temperature was 140 K. With poor hole confinement in the multi-quantum well active region and only 2 stages, differential quantum efficiencies > 1 (photon/injected carrier) have not been observed for the multi-stage, pseudomorphic InAsSb devices.

Figure 4 - Lasing spectra of the type II, InAs/GaInSb cascaded laser at 80 K and 120K under pulsed operation, 0.01% duty cycle.[3]

In contrast, emission from a 20 stage, type II InAs/GaInSb laser (see Fig. 1b) is shown in Fig. 4.[3] Similar to the InAsSb devices, electron-hole pairs are generated in each stage at an InAs(n)/AlSb/GaSb(p) semi-metal layer with a thin (20 Å) AlSb tunnel barrier. Unlike the InAsSb devices, electrons and holes injected into the InAs/GaInSb lasing states cannot escape. The electrons and holes must recombine either radiatively or nonradiatively at the type II, lasing transition. With "perfect" carrier confinement and 20 stages, differential quantum efficiencies of 1.3 (photon/injected carrier) have recently been reported for these type II cascaded lasers.[4] Despite this advance, the type II cascaded lasers still exhibit large threshold currents and turn-on voltages, producing unmanageable heating. Subsequent, 3.8 μm type II devices display pulsed operation up to 165 K and have a threshold current density of 3 kA/cm² at 80 K.[4]

Discussion

The unipolar quantum cascade laser illustrates the value of using multiple, cascaded lasing transitions to increase gain and to overcome high non-radiative recombination rates. Optimizing the performance of the cascaded design, recent unipolar quantum cascade lasers approach "perfect" carrier confinement with the development of "Bragg reflectors" that prevent electrons injected into the lasing state from escaping to the continuum.[5] Also, electron transport in the unipolar quantum cascade laser is very efficient, with turn-on voltages approaching $N \cdot \hbar\omega$ (N is the number of stages, and $\hbar\omega$ is the laser emission energy).

In Sb-based active regions with poor hole confinement, like pseudomorphic InAsSb multiple quantum wells with InAs barriers, multi-staging is a convenient method for generating multi-color emission. (Adequate electron confinement is provided by the AlAsSb barrier as in Fig. 1a) However, multi-staging of pseudomorphic InAsSb lasers would be equivalent to growing a thick active region to increase gain, and differential quantum efficiencies >1 should not be expected. Instead, multi-staging should prove effective to increase gain from active regions with larger valence band offsets and improved hole confinement, such as InAsSb quantum wells with InAsP barriers, where injection laser studies indicate that holes diffuse over <10 quantum wells.[6] Development of MOCVD-grown, multi-staged InAsSb/InAsP quantum well lasers are in progress.

To overcome non-radiative recombination, mid-infrared lasers will require higher threshold currents and produce larger heat loads than comparable, shorter wavelength devices. If the voltage drop per stage greatly exceeds $\hbar\omega$, too much heat will be produced in a multi-stage laser to realize any benefit from the increased gain. In each stage, barriers like that produced by the AlAsSb/GaAsSb valence band offset in InAsSb devices (Fig. 1a) or by heavy hole tunnelling through AlSb layers in type II devices (Fig. 1b) can produce unwanted charge build-up and voltage drops. More efficient carrier transport is required to demonstrate practical, Sb-based multi-stage lasers. Initial results indicate that turn-on voltages of multi-staged InAsSb devices may be controlled with heterobarrier doping and grading.

Summary

Using a semi-metal, GaAsSb(p) / InAs (n) heterojunction as an internal electron-hole source, interband multi-stage lasers and LEDs have been demonstrated which emit at 4 μm . An MOCVD-grown, 2-stage LED and a 2-stage laser with pseudomorphic InAsSb quantum well active regions are described and compared with recently demonstrated type II InAs/GaInSb "cascaded" devices. Improved carrier confinement and efficient carrier transport in multi-stage active regions are critical to achieve differential quantum efficiencies >1 and to demonstrate "cascaded" mid-infrared lasers with manageable heating.

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References

- [1] Allerman A A, Kurtz S R, and Biefeld R M 1996 *Appl. Phys. Lett.* 69 465-7
- [2] Meyer J R, Vurgaftman I, Yang R Q, and Ram-Mohan L R 1996 *Electron. Lett.* 32 45-6
- [3] Lin C H, Yang R Q, Zhang D, Murry S J, Pei S S, Allerman A A, and Kurtz S R 1997 *Electron. Lett.* 33 598-9
- [4] Yang R Q, Yang B H, Zang D, Lin C H, Murry S J, Wu H, and Pei S S (submitted for pub.)
- [5] Faist J, Capasso F, Sirtori C, Sivco D L, Hutchinson A L, and Cho A Y 1995 *Appl. Phys. Lett.* 66 538-40
- Sirtori C, Faist J, Capasso F, Sivco D L, Hutchinson A L, and Cho A Y 1997 *IEEE Photon. Tech. Lett.* 9 294-6
- [6] Kurtz S R, Allerman A A, and Biefeld R M 1997 *Appl. Phys. Lett.* 70 3188-90
- Kurtz S R, Allerman A A, and Biefeld R M (unpublished)