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Optical gain calculation of mid-infrared InAsN/GaSb quantum-well laser for tunable absorption spectroscopy applications

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Abstract

We report on optical gain calculations of a dilute-nitride mid-infrared laser structure designed to be grown on InAs substrate. The active region is composed of several strain-compensated type-II “W”-like InAsN/GaSb/InAsN quantum wells adapted to operate near 3.3 μm at room temperature. For typical injected carrier density $\sigma = 1.1012\ \text{cm}^{-2}$, the theoretical laser structure performances reveal a gain value at around 1000 cm^{-1} at 300 K, inducing a modal gain value equal to 50 cm^{-1}. Low radiative current densities lower than 100 A/cm^2 are predicted, indicating that this dilute-nitride structure could operate at 300 K with small threshold current density.

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1. Introduction

Laser diodes emitting in the mid-wave infrared (MWIR) domain (3–5 μm) arouse a growing interest due to their potential applications especially for gas analysis by tunable diode laser absorption spectroscopy (TDLAS) suitable for environmental surveillance. Indeed, there exist many polluting gases and combustion products with strong absorption lines in the MWIR region such as CH_4 (3.3 μm), HCHO (3.5 μm), HCl (3.5 μm), NO_2 (3.9 μm and 4.5 μm), SO_2 (4.0 μm), CO_2 (4.25 μm) and CO (4.6 μm). For TDLAS measurements, high performance laser structures operating at room temperature (RT) in continuous wave (CW) regime are required with single optical mode emission. To reach this objective, impressive progress has been made recently by using highly sophisticated interband [1] and intraband [2] quantum-cascade lasers. But more conventional antimonide (Sb) based lasers using type-I [3] and type II “W”-like [4] multi-quantum well (MQW) structures are also very promising to reach high performance operation and to satisfy requirements for gas sensing in the 3–5 μm range [5].

In this paper, we report a theoretical investigation on a new class of dilute-nitride type-II “W”-like InAsN/GaSb/InAsN laser structure designed to be grown on InAs substrate and to operate at around 3.3 μm at RT. To estimate the ability of this new MQW laser to achieve stimulated emission at RT, we calculate the modal gain and the radiative current density extracted from optical gain calculations in TE mode polarization emission.

This structure presents several advantages. First, the “W” arrangement induces a phase position of the carriers that increases the electron-hole overlap integral and hence the optical matrix elements, giving values comparable to type-I structures. Next, because of the small in-plane electron and hole masses and the elimination of the resonance between the energy gap and the spin–orbit splitting energy or with any energy resulting from lower valence subbands, a strong reduction of Auger recombination rate has been predicted in structure combining type-II band alignment with dilute nitrogen compounds [6]. Finally, this MQW structure with active zone composed by a few periods of “W” stack can be easily fabricated by molecular beam epitaxy.

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2. Dilute-nitride "W" laser design

The dilute-N InAsN/GaSb/InAsN laser structure is strain-compensated on InAs substrate and is tailored for RT operation around 3.3 µm. The active zone is composed of several strain-compensated periods where a GaSb quantum well is surrounded by two dilute-nitride $InAs_{0.96}N_{0.034}$ quantum wells. This forms a conduction band and a valence band profile in the shape of a "W" as one can see in the schematic band diagram presented in Fig. 1. The dilute-nitride compound induces deep quantum wells with high band offset value allowing strong confinement of both types of carriers. The InAsN and GaSb layer thickness, respectively equal to 25 Å and 15 Å, are chosen to exhibit laser emission around 3.3 µm with the highest electron-hole wavefunction overlap value. In order to ensure a two dimensional behavior of carriers all over the structure, each "W" quantum well strain-compensated period is separated by a 200 Å-thick $Al_{0.3}Ga_{0.7}As_{0.05}Sb_{0.95}$ spacer layer lattice matched to InAs. These MQWs are embedded in an undoped 0.5 µm $Al_{0.3}Ga_{0.7}As_{0.05}Sb_{0.95}$ waveguide layer. The use of this broadened waveguide maximizes the optical confinement factor and minimizes free-carrier absorption losses in the $Al_{0.9}Ga_{0.1}As_{0.14}Sb_{0.86}$ cladding layer. This cladding layer, lattice matched to InAs substrate, provides good optical confinement and high type-I band-offset, reducing carrier leakage current.

The RT band diagram of the InAsN (25 Å)/GaSb (15 Å)/InAsN (25 Å) "W" structure and the fundamental electron (e_1) and heavy hole (hh_1) energy levels and their respective f^2_{e1} and f^2_{hh1} carriers probability densities are shown in Fig. 1. Conduction and valence band-offset (ΔE_c and ΔE_v) and numerical values used in the calculations were extracted from the literature [7]. The computation of the electrons and holes energy levels was performed using the **k**.**p**. formalism and the envelope function approximation. The calculated emission wavelength is expected at 3.3 µm at RT, with a carrier wavefunction overlap value of 71%.

3. Optical gain calculation of dilute-nitride "W" laser

The optical gain per dilute-N "W" period was calculated according to reference [8] for different injected carrier densities s in the active region, varying from $\sigma = 0.25\ 10^{12}$ to $2.5\ 10^{12}\ cm^{-2}$. Calculations were made only for the TE mode with an intraband relaxation time of 10^{-13} s, neglecting band mixing and many body effects. Coulomb attraction between electrons and holes was taken into account by solving the coupled Poisson and Schrödinger equation under injection. RT gain results are shown in Fig. 2 and maximal gain values extracted from optical gain curves are reported in the inset of Fig. 2. For typical injected carrier density of 1.10^{12} cm-^{2}, maximal gain value at around 1000 cm^{-1} is obtained. One can note that it is necessary to inject at least $\sigma = 0.2\ 10^{12}\ cm^{-2}$ charges to satisfy the well-known Bernard–Durrafourg's condition.

Gain curves are similar to the ones obtained on GaAsN-based "W" structures on GaAs substrate for emission at around 1.55 µm [9] but gain values are higher than the results extracted from calculations performed on Sb-based "W" structures on InAs substrate for emission at around 3.3 µm [10].

RT modal gain G_{mod} of the structure was calculated by using the following relation: $G_{mod} = N_p\ \Gamma_p\ G_{max}$ where G_{max} is the peak gain value extracted from the gain curves (inset of Fig. 2), N_p is the number of "W" periods taken equal to 5 and G_p is the optical confinement factor per double QW for which the calculated value is equal to 1.74%. Results as function of carrier

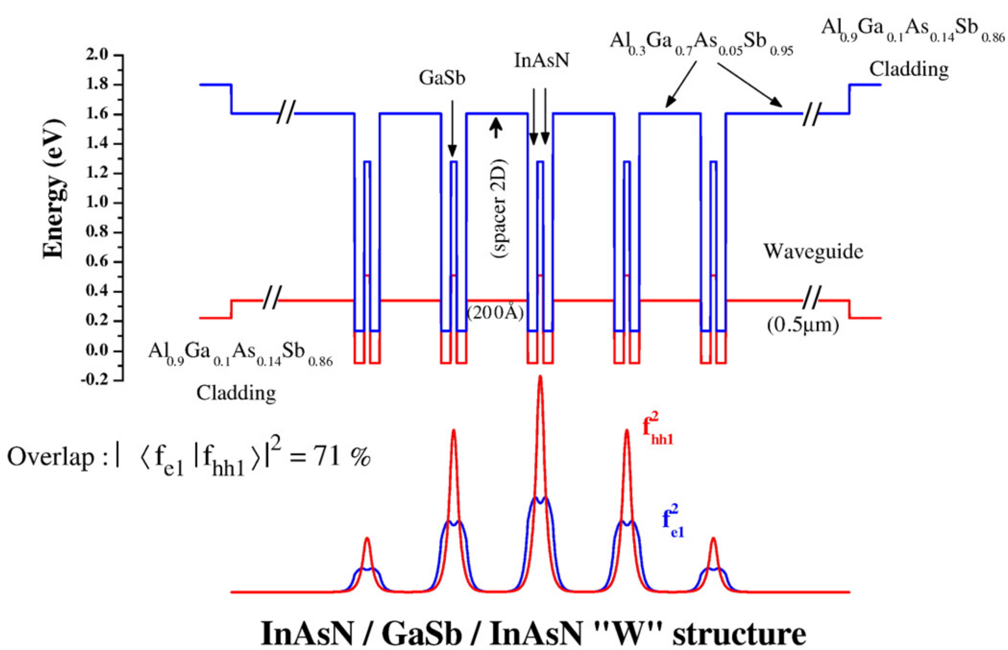

Fig. 1. RT conduction and valence band profiles of the $InAs_{0.96}N_{0.034}$ (25 Å)/GaSb (15 Å)/$InAs_{0.96}N_{0.034}$ (25 Å) "W" laser structure strain-compensated on InAs substrate. On the lower part, fundamental electron (e_1) and heavy hole (hh_1) presence probability densities are reported. The $e_1 - hh_1$ optical transition is expected at 3.3 µm with an overlap value $|\langle f_{e1}|f_{hh1}\rangle|^2 = 71\%$.