Influence of Device Structures on Carrier Recombination in GaAsSb/GaAs QW Lasers

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Abstract—We investigate the temperature and pressure dependence of carrier recombination processes occurring in various GaAsSb/GaAs QW laser structures grown under similar growth conditions. Thermally activated carrier leakage via defects is found to be very sensitive to the strain induced interface imperfections. Nonradiative recombination is found to be sensitive to the number of QWs. A strain compensated MQW structure leads to a reduced contribution of non-radiative recombination to the threshold current density (J_{th}) and a high characteristic temperature (T_0) of 73K at room temperature.

I. INTRODUCTION

Semiconductor lasers emitting at $\sim 1.3 \mu\text{m}$ are key for the rapid expansion of next generation metro-area networks. Vertical cavity surface-emitting lasers (VCSELs) operating at this wavelength have been of great interest due to their high performance and low cost manufacturing process. The conventional InGaAsP/InP QW material system used to make such lasers suffers from two problems: Firstly the poor thermal properties of InP-based lasers result in the need to incorporate sophisticated temperature control electronics into the package, leading to an order of magnitude increase in cost [1]. Secondly, due to the lack of lattice matching and high refractive index contrast materials to form all-epitaxial distributed Bragg reflectors (DBRs), it is also very difficult to fabricate monolithic VCSELs in the InP material system [2] [3]. On the other hand, GaAs permits the growth of lattice-matched GaAs/AlGaAs DBRs, which have superior optical and thermal properties when compared to other III-V DBRs [4]. Furthermore, the fabrication of GaAs based $1.3 \mu\text{m}$ VCSELs can take full advantage of the industrial standard 850 nm VCSEL fabrication technology, which is attractive from a manufacturing point of view. Lasers (edge emitting [5] and VCSELs [6]) based upon this material have been an active research area due to their high potential for $1.3 \mu\text{m}$ active regions on a GaAs substrate [7]–[10]. However difficulty in growing high-quality GaAs_{1-x}Sb_x/GaAs QW active material for $1.3 \mu\text{m}$ operation is one of the main challenges to make this material system commercially viable [11] [12]. This paper investigates the role of device structure design on the carrier recombination and efficiency limiting processes in GaAs_{1-x}Sb_x/GaAs QW lasers to aid in the optimization of GaAsSb/GaAs-based edge-emitting lasers and VCSELs.

II. LASER STRUCTURE

The devices in this study were grown using solid source MBE under similar growth conditions. Device A has an active region containing one GaAs/GaAs_{0.7}Sb_{0.3}/GaAs (15nm/7nm/15nm) strained QW, device B has an active region containing one GaAs_{0.9}P_{0.1}/GaAs/GaAs_{0.7}Sb_{0.3}/GaAs/GaAs_{0.9}P_{0.1} (8nm/3nm/7nm/3nm/8nm) strain compensated QW, and device C has an active region containing two QWs of the same structure as device B. The GaAsP layers in device B and C provide strain compensation to increase the maximum number of highly strained QWs that can be grown pseudomorphically and to reduce strain driven in-plane Sb segregation that leads to inhomogeneous linewidth broadening. The active region in each device is sandwiched between two 20 nm Al_{0.25}Ga_{0.75}As layers, two 150 nm graded-index (GRIN) AlGaAs layer with Al concentration linearly increased from 25% to 65%, one $2 \mu\text{m}$ n -type (Si doped, $2 \times 10^{18} \text{ cm}^{-3}$) Al_{0.65}Ga_{0.35}As cladding layer followed by 500 nm GaAs buffer layer at bottom, and one $2 \mu\text{m}$ p -type (Be doped, $2 \times 10^{18} \text{ cm}^{-3}$) Al_{0.65}Ga_{0.35}As cladding layer followed by 100 nm GaAs cap layer at top. The doping concentration is decreased from $2 \times 10^{18} \text{ cm}^{-3}$ to $1 \times 10^{17} \text{ cm}^{-3}$ in both GRIN layers from cladding layer to active region and is increased to $2 \times 10^{19} \text{ cm}^{-3}$ in GaAs cap layer from cladding layer to surface. The devices are fabricated using a typical broad contact edge-emitting laser process. The device ridges (50 and 100 μm wide) were defined using photolithography and inductively coupled plasma dry etching. By etching down through the p -GaAs contact layer and stopping about 0.1 μm above the active region, these ridges provide current confinement as well as waveguiding. Ti/Pt/Au p -contact stripes ranging from 2 to 32 μm were deposited using a second mask, after which the wafers are lapped down to 100 μm and AuGe/Ni/Au n -metal contacts are deposited on the backside of the substrate; this is followed by rapid thermal annealing for both metal contacts. The devices were measured as cleaved and room temperature (RT) emission wavelength was measured to be $1.25 \mu\text{m}$ in these devices.

III. EXPERIMENTS

Temperature dependence measurements over the range of 60–300K were performed with a standard closed cycle

cryostat set-up. Hydrostatic pressure measurements over the range 0–8.5 kbar were performed using a gas compressor system. Carrier recombination mechanisms are influenced by the band structure. Conventional methods to change the band structure to investigate the recombination mechanisms, involve growing a series of devices with a range of active region alloy compositions. The high costs involved with growing a lot of wafers, the difficulty in keeping doping densities and layer thicknesses identical mean this method can be unreliable. By using high hydrostatic pressure to reversibly alter the band-structure of one device, the recombination mechanisms can be quickly and easily resolved. The application of high hydrostatic pressure causes an increase in the direct band gap, mimicking the effect of alloying thereby allowing one to investigate wavelength dependent properties of semiconductor lasers. Furthermore, due to the different pressure coefficients of the layers it can also be used to alter the alignment between direct (Γ) and indirect (X, L) bands and to alter the band offsets between layers of differing composition [5]. In order to quantify the different carrier recombination processes, we also measured the pure spontaneous emission from the lasers. Since the light emitted from the facets is strongly influenced by gain/loss as the optical field propagates along the cavity, we instead measure the light emitted in a perpendicular direction. To do this we milled a window in the n-side of the devices using a focused ion beam and aligned an optical fibre with the window to collect the spontaneous emission where the coupling efficiency is kept constant. This experiment was performed as a function of temperature. Further details of this technique are described elsewhere [13].

IV. TEMPERATURE DEPENDENCE

The threshold current of a semiconductor laser is the point at which the gain equals all of the losses in the device and above this current efficient stimulated emission dominates. It is therefore desirable to have a low (ideally zero) and temperature independent threshold current [5]. Figure-1a shows the normalized (at $T=60\text{K}$) temperature dependence of the J_{th} of device A, B and C, which increase superlinearly with increasing temperature, suggesting a thermally activated recombination process is becoming dominant at higher temperature in these devices. Figure-1 also shows the temperature dependence of the radiative current density (J_{rad}), which is extracted from the pinning level of the measured integrated spontaneous emission. It is found that J_{rad} has an almost linear temperature dependence as expected for an ideal QW laser (figure-1b). This implies that the loss mechanisms must increase superlinearly with increasing temperature in these devices. From the measured J_{th} and J_{rad} , we estimate that the relative ratio of the radiative (non-radiative) currents at J_{th} are $\sim 16\%$ ($\sim 84\%$), $\sim 27\%$ ($\sim 73\%$) and $\sim 33\%$ ($\sim 67\%$), at RT, for device A, B and C respectively. Thus, a non-radiative recombination process dominates J_{th} at RT in these devices. A higher J_{rad}/J_{th} in device B and C than that of device A may be due to the use of $\text{GaAs}_{0.9}\text{P}_{0.1}$ strain compensation layer to improve the

interface quality by reducing interface imperfection. A higher J_{rad}/J_{th} in device C than that of device B may be due to a reduced non-radiative recombination path in the MQW devices. The characteristic temperature (T_0) is a measure of temperature stability of threshold current and can be derived from the relation:

$$\frac{1}{T_0} = \frac{d \ln(J_{th})}{dT} \quad (1)$$

From figure-1a, we find that the T_0 (derived from equation-1) for device A, B and C are 51K, 66K and 73K respectively.

Fig. 1. (a) Normalised (at $T=60\text{K}$) temperature dependence of J_{th} . (b) Temperature dependence of J_{rad} has almost ideal QW linear temperature dependence.

T_0 (at RT) in device A is approximately the same as that of conventional InGaAsP/InP devices (typically $\sim 50\text{--}60\text{K}$ near RT) and lower ($\sim 51\text{K}$) than that for device B ($\sim 66\text{K}$) and device C ($\sim 73\text{K}$) over a temperature range of 240–300K. A higher T_0 in device C compared to device B is consistent with a reduced non-radiative recombination path in the MQW devices.

V. PRESSURE DEPENDENCE

Light-current characteristics were measured at RT for pressures 0-7kbar, and corresponding threshold current (J_{th}) values were determined in the normal way. Lasing wavelengths (λ) with pressure were measured at $1.1I_{th}$. Figure-2 shows the measured pressure dependence of J_{th} at RT. Also shown is the ideal expected variation of $J_{rad} \propto E_g^2$ [14], where E_g is the bandgap (taken from $E_g = hc / \lambda$). J_{th} and J_{rad} have been normalized to their

Fig. 2. Pressure dependence of threshold current density. Also shown is the ideal expected variation of radiative current with pressure.

respective values at atmospheric pressure. Our calculated pressure co-efficient based on measured wavelength is 7.7 meV/kbar for these devices, in agreement with previously measured strain compensated GaAsSb/GaAs QW devices [1, 5]. Preliminary pressure measurements suggest that the pressure dependence of J_{rad} in this material system is very close to ideal [15]. It can be clearly seen that the threshold current increases with pressure much faster than J_{rad} , which confirms that the lasers are not operating in a radiatively dominated regime and suggesting the presence of carrier leakage in these devices. The threshold current for device A, B and C increased by ~37%, ~52% and ~63% respectively up to 7 kbar at RT. The higher rate of increase in J_{th} in device B and C compared to device A may be due to the use of GaAs_{0.9}P_{0.1} strain compensation layer in devices B and C decreases the concentration of defects. The fact that J_{th} for device A has a stronger temperature dependence, but weaker pressure dependence indicates that the defect levels are shallow. The higher rate of increase in J_{th} in device B than that of device C is also consistent with reduced non-radiative recombination in the MQW devices.

VI. CONCLUSIONS

In summary, we have investigated the temperature and pressure dependence of carrier recombination process

occurring in various GaAsSb/GaAs QW laser structures. A strain compensating layer in the active region leads to an improvement in the radiative recombination process from ~16% to ~27% of J_{th} and higher T_0 from 51K to 66K at RT. A MQW structure further decreases the contribution of non-radiative recombination and increases T_0 from 66K to 73K at RT. Optimization of 1.3μm GaAsSb/GaAs QW lasers will rely upon reducing the thermally activated carrier leakage via the defect states and by careful design of the laser structure.

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