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Research Article

DETERMINATION OF SPONTANEOUS EMISSION RATE AND CARRIER RECOMBINATION CHANNELS IN GaInAsSb/AlGaAsSb MULTIPLE QUANTUM WELL LASER DIODES EMITTING NEAR 2.3 µm

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ABSTRACT

In this paper, Amplified spontaneous emission spectra is used to extract the gain and internal loss of 2.3 µm narrow ridge-waveguide GaInAsSb-AlGaAsSb quantum well laser diodes by Cassidy's method. The spontaneous emission intensity was extracted using the average value of the amplified spontaneous emission intensity. The dependence of the integrated spontaneous emission intensity on injection current has been studied. The results show that the current is dominated by radiative recombination at this emission wavelength.

Keywords: Amplified spontaneous emission; Spontaneous emission; Gain; Recombination.

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1. INTRODUCTION

Compact semiconductor laser sources emitting at room temperature in continuous-wave (CW) in the mid-infrared (2–5 µm) are needed for various applications such as gas sensing, medical diagnostics or security screening [1]. GaSb-based laser diodes (LDs) are currently the best lasers for these applications [2]. A detailed knowledge of the physical parameters governing the behaviour of such LDs is crucial to improve their design and performance. An efficient way to achieve a thorough understanding of LDs is to extract the optical gain from the emission spectrum of the devices. This measurement supplies much information such as the internal loss, the transparency current density and the gain coefficient [3]. Up to now however, little attention has been paid to the information that can be determined from the spontaneous emission data present in the spectrum.

In the past three decades, different methods have been developed to extract the gain from the amplified spontaneous emission (ASE) spectrum emitted by a diode below its threshold current [4-6]. A common method was proposed by Hakki and Paoli [4]. The net modal gain g_{net} is determined from the contrast of the ASE spectra, i.e. the ratio of the minimal and maximal intensity of each longitudinal mode in the spectrum. This method critically depends on the spectrometer resolution: a low-resolution results in a flattening of the top of each mode and leads to an erroneously low gain. Cassidy derived a modification of Hakki-Paoli's method [5]. Instead of using the maximum and minimum intensities, Cassidy calculates the ratio of the intensity integrated over one mode to the mode minimum intensity. This approach, the so-called mode-sum method, is less sensitive to the spectral resolution than Hakki and Paoli's method.

In this paper, we use the Cassidy approach to determine the net modal gain and the internal loss of a 2.3 µm GaInAsSb-AlGaAsSb multi-quantum-well (MQW) laser diode. We propose a method to extract the spontaneous emission (SE) spectrum from the ASE spectrum. The SE spectrum is then transformed into a spontaneous recombination rate spectrum whose integration gives a parameter proportional to the total spontaneous recombination rate. Plotting the current as a function of the square root of this value enables to highlight the principal electron-hole recombination mechanism at work in the LD.

2. METHOD

The first step of the method consists in extracting the gain from the ASE spectrum thanks to Cassidy's procedure. g_{net} is determined from the ASE by (1) [5, 6]:

$$g_{net}(\lambda) = \frac{1}{L} \ln \frac{p(\lambda)-1}{p(\lambda)+1} \tag{1}$$

where L is the laser resonator length, and…

$$p(\lambda) = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda') d\lambda'}{I_{\min}(\lambda) \cdot (\lambda_2 - \lambda_1)} \tag{2}$$

…is the ratio of the integral of the intensity over one mode (from one minimum to the next one) to the mode minimum. The net modal gain is related to the modal gain by:

$$g_{net}(\lambda) = g(\lambda) - \alpha_i - \alpha_m \tag{3}$$

where α_i is the internal loss and α_m, the optical mirror loss. In a symmetric Fabry-Perot (FP) cavity, the mirror loss equals:

$$\alpha_m = 1/L \cdot \ln(1/R) \tag{4}$$

where R is the mirror reflectivity.

We then define the single pass gain g_{sgl} as:

$$g_{sgl}(\lambda) = g(\lambda) - \alpha_i \tag{5}$$

From (3), g_{sgl} can be calculated as:

$$g_{sgl}(\lambda) = g_{net}(\lambda) + \alpha_m \tag{6}$$

The second step of the method consists in extracting the spontaneous emission intensity from the ASE spectrum. The ASE spectrum of a FP semiconductor laser can be described by the following Airy function [5-8]:

$$I(\lambda) = \frac{I_{sglase} \cdot [1 + R \cdot \exp(g_{sgl} \cdot L)] \cdot (1-R)}{1 + [R \cdot \exp(g_{sgl} \cdot L)]^2 - 2R \cdot \exp(g_{sgl} \cdot L) \cdot \cos\left(\frac{2\pi\lambda}{FSR}\right)} \tag{7}$$

where I_{sglase} is the spontaneous emission coupled into the lasing mode and amplified by a single pass inside the cavity, FSR is the free spectral range ($FSR = \lambda^2/2.n_{gr}.L$), and n_{gr} is the group index of the laser structure. The average value of $I(\lambda)$ over one free spectral range can be calculated from (7) and is given by:

$$\langle I(\lambda)\rangle = \frac{I_{sglase}\cdot(1-R)}{1-R\cdot\exp\left(g_{sgl}\cdot L\right)} \tag{8}$$

Yet:

$$\left\langle \frac{A}{B+C\cdot\cos\left(\frac{2\pi\lambda}{FSR}\right)}\right\rangle = \frac{1}{FSR}\int_{\lambda}^{\lambda+FSR}\frac{A}{B+C\cdot\cos\left(\frac{2\pi\lambda}{FSR}\right)}d\lambda = \frac{A}{\sqrt{(B+C)(B-C)}} \tag{9}$$

because one free spectral range corresponds to one period of oscillation.

From (8), one obtains:

$$I_{sglase}(\lambda) = \frac{\langle I(\lambda)\rangle\cdot\left[1-R\cdot\exp\left(g_{sgl}\cdot L\right)\right]}{1-R} \tag{10}$$

When knowing g_{sgl}, calculating the moving average of $I(\lambda)$ leads to the value of I_{sglase}.

The spontaneous emission into the mode per unit path length I_{sp} is then determined from [9]:

$$I_{sp}(\lambda) = \frac{g_{sgl}\cdot I_{sglase}(\lambda)}{\exp\left(g_{sgl}\cdot L\right)-1} \tag{11}$$

If I_{sglase} is expressed in W, I_{sp} is expressed in W.cm^{-1}. Equation (11) is valid for both transverse-electric (TE) and transverse-magnetic (TM) modes. But the material gain for the TE modes is higher than for TM modes [10].

The spontaneous emission rate $r_{sp}(\lambda)$ spectrum can be extracted from the spontaneous emission intensity by [11, 12]:

$$r_{sp}(\lambda) = \frac{\lambda\cdot I_{sp}(\lambda)}{h\cdot c\cdot K\cdot\Delta\lambda\cdot A} \tag{12}$$

where h is Plank's constant, c is the speed of light, K is a coupling coefficient which includes the fraction of ASE captured by the detector, $\Delta\lambda$ is the spectrometer resolution and A is the active region surface (the length of the laser multiplied by its width). If hc/λ is expressed in J, $d\lambda$ in cm and A in cm^2, $r_{sp}(\lambda)$ will be expressed in cm^{-3}.s^{-1}.cm^{-1} because $r_{sp}(\lambda)$ is a rate spectrum and therefore has dimensions number per unit wavelength interval per unit volume per unit time ([L]$^{-4}$[T]$^{-1}$).

There is a way to determine the value of K, the unknown fraction of the spontaneous emission detected by the photodiode. Indeed, there is a relationship linking the modal gain and the spontaneous emission rate [11]:

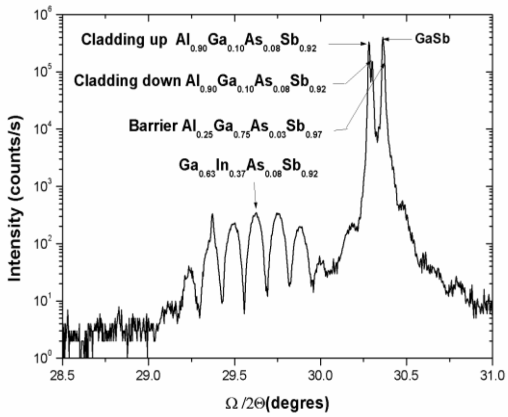
$$g(\lambda) = \frac{\Gamma \cdot \lambda^4}{8\pi \cdot cn^2}\left[1 - \exp\left(\frac{\frac{hc}{\lambda} - \Delta E_f}{kT}\right)\right] \cdot r_{sp}(\lambda) \qquad (13)$$

where *Γ* is the optical confinement factor, *c*, the speed of light, *n*, the effective refractive index, ΔE_f, the quasi-Fermi level separation energy, *k*, the Boltzmann's constant, *T*, the temperature and $r_{sp}(\lambda)$ is substituted from (12). For calibrating r_{sp}, it is hence sufficient to find the values of *K* and ΔE_f allowing to fit the experimental $g(\lambda)$ curve with the $g(\lambda)$ curve deduced from $I_{sp}(\lambda)$. Once these parameters have been found, integrating r_{sp} directly leads to the value of the the radiative current density J_{rad}.

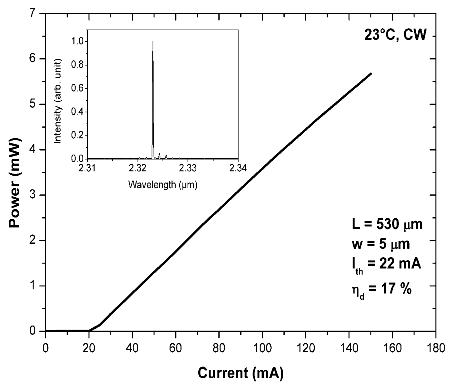
3. EXPERIMENTAL DETAILS

We have applied this approach to a GaInAsSb/AlGaAsSb ridge-waveguide multiple quantum-well (QW) LD emitting at 2.32 µm. The laser structure was grown by molecular beam epitaxy (MBE) on an *n*-type (001)-GaSb substrate using a valved cracking cell producing As_2 molecules and a standard Sb_4 effusion cell. Layers of the structure were grown in the following order: a 75 nm-thick *n*-type GaSb buffer (2 x 10^{18} cm^{-3}, Te), a 100 nm-thick *n*-type layer graded from $Al_{0.10}Ga_{0.90}As_{0.03}Sb_{0.97}$ to $Al_{0.90}Ga_{0.10}As_{0.08}Sb_{0.92}$ (2 x 10^{18} cm^{-3}, Te), a 1.5 µm-thick *n*-type $Al_{0.90}Ga_{0.10}As_{0.08}Sb_{0.92}$ (2 x 10^{18} cm^{-3}, Te) cladding layer, an undoped active zone consisting of two 10 nm-thick 1.5 % compressively strained QWs of $Ga_{0.63}In_{0.37}As_{0.08}Sb_{0.92}$ separated by 40 nm-thick $Al_{0.25}Ga_{0.75}As_{0.03}Sb_{0.97}$ barriers and enclosed between 370 nm-thick $Al_{0.25}Ga_{0.75}As_{0.02}Sb_{0.98}$ spacers, a 1.5 µm-thick *p*-type $Al_{0.90}Ga_{0.10}As_{0.08}Sb_{0.92}$ cladding layer (5 x 10^{17} cm^{-3} for the first 200 nm and 2 x 10^{18} cm^{-3} for the remaining 1.3 µm, Be), a 100 nm-thick *p*-type layer graded from $Al_{0.90}Ga_{0.10}As_{0.08}Sb_{0.92}$ to $Al_{0.10}Ga_{0.90}As_{0.03}Sb_{0.97}$ and finally a 0.25 µm p^+-GaSb (2 x 10^{19} cm^{-3}, Be) cap layer. The growth of the whole structure was carried out at a temperature of 480 ^oC. The x-ray diffraction measurements showed high crystalline quality of the grown wafer (Fig. 1(a)).

Fabry-Perot lasers with 5 µm wide metal contact stripes were fabricated. The choice of the narrow wide waveguide (5 µm) device is to have a lateral monomode emission. Uncoated facets and cavity length cavity 530 µm were used in this work. The LD was mounted *p*-side down, or epi-down, onto a copper heatsink and characterized in the CW regime. Fig. 1(b) shows the light-current (P-I) characteristic of this LD at room temperature. The inset in Fig. 1(b) shows the laser spectrum taken at 30 mA drive current with an emission centered at 2.323 µm with few, weak, side modes visible. A threshold current of 22 mA is obtained. This value corresponds to a threshold current density of 830 A/cm^2 for a narrow ridge waveguide diode of 5 µm and 530 µm of length (5 µm x 530 µm). This current density is comparable to the best DFB-GaInAsSb/AlGaAsSb-(4 µm x 400 µm) threshold current density reported [13]. However, it remains very high compared to the threshold current density obtained on the broadened-waveguide diode lasers. This is due to the presence of the leakage currents on either side of the stripe. Furthermore, the emitted power (around 6 mW) and the differential efficiency (17 %) are very low because of a high thermal resistance due to the smallness of the stripe [14].



(a)



(b)

Fig.1. (a) High-resolution XRD diagram of the laser structure, (b) CW P-I characteristic of a 530-µm long and 5-µm-wide laser diode at room temperature (the insert shows a spectrum recorded at 30 mA)

The ASE spectra were measured using a 1.5 m Cznery-Turner grating monochromator. The light emitted from the front LD facet was modulated by a mechanical chopper (1 kHz) and focused by one lens (*f* = 2 cm) onto the entrance slit of the monochromator. An InGaAs photodetector (Hamamatsu G5853-11) connected to a lock-in-amplifier was used for measuring the emitted power. The ASE spectra were collected directly in the front of the detector without polarizer and so, TE and TM modes are collected simultaneous. The TE mode is naturally preponderant in this compressively strained QWs lasers because the transition is governed by heavy-holes [10, 15, 16]. The spectra were measured with a resolution $\Delta\lambda$ of 0.2 nm. To determine $\Delta\lambda$ experimentally, it is sufficient to do the spectrum of monomode laser and measure the FWHM of the obtained spectrum. All LD characterizations have been performed under CW at 23°C.

4. RESULTS AND DISCUSSION

We measured the ASE spectra for different injection currents below threshold. The ASE spectrum measured at injection of 21 mA is shown in Fig. 2. The net modal gain was extracted thanks to (1) at each injection current. Fig. 3 shows the net modal gain spectra for currents between 15 and 21 mA. One can determine the total optical losses ($\alpha_{tot} = \alpha_i + \alpha_m$) from the value of the net modal gain on the long wavelength side of the graph, where all curves converge, which corresponds to a modal gain equal to zero (g = 0).

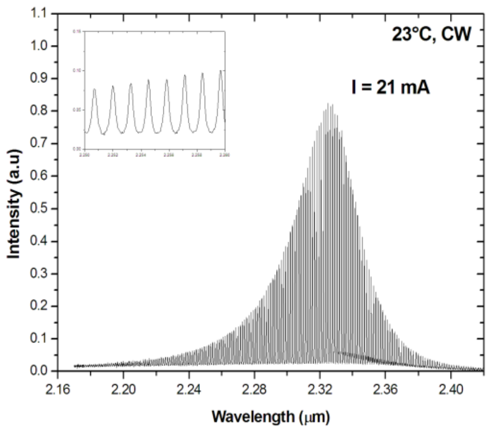


Fig.2. Measured amplified spontaneous emission spectrum of 21 mA at 23°C, the inset shows the zoom of the spectrum

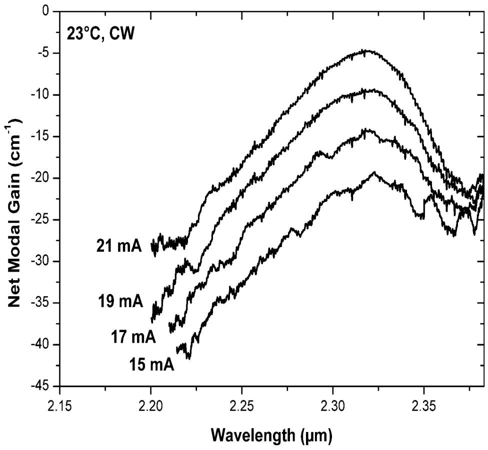


Fig.3. Net modal gain spectra at injection currents of 15, 17, 19 and 21 mA

From Fig. 3, one extracts total optical losses of α_{tot} = 24 ± 1 cm^{-1}. Using a mirror reflectivity of 0.33 (since the effective index of the amplifying medium is typically of 3.50) and (4), we calculate an internal loss as low as α_i = 3 ± 1 cm^{-1}. The peak net modal gain is plotted in Fig. 4 as a function of injection current.

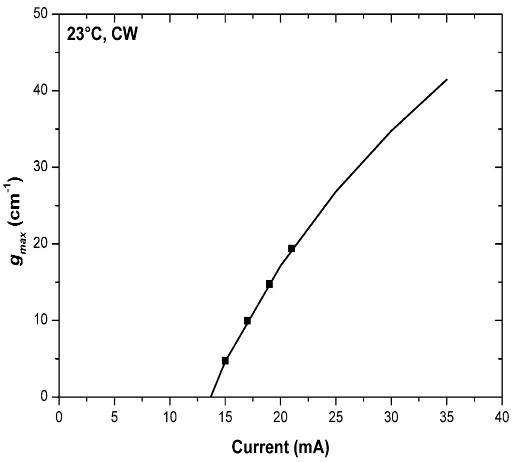


Fig.4. Maximal net modal gain versus injection current

The transparency current density J_{tr} and the modal gain coefficient $\Gamma{\cdot}G_0$ as a function of current density J were obtained by fitting the experimental data of Fig. 3 with the following equation [10]:

$$g_{\max} = \Gamma \cdot G_0 \ln\left(\frac{J}{J_{tr}}\right) \qquad (14)$$

where G_0 is the material gain coefficient and Γ is the optical confinement factor.

Equation (14) yields a transparency current density of 490 A/cm^2 and a modal gain coefficient of 43 cm^{-1}. Thus, the transparency current density and the modal gain coefficient per QW are 245 A/cm^2 and 21.5 cm^{-1}, respectively. The value of the transparency current density per QW is high compared to the broadened-waveguide (100-µm-wide) diode lasers [17, 18] due to the presence of the leakage currents in the case of narrow waveguide.

The comparison between the threshold current density obtained directly by (P-I) characteristic and the one obtained by our gain extraction method was done to check the efficiency of our method. The threshold current density J_{th} can be calculated using the expression [19]:

$$J_{th} = J_{tr} \exp\left(\frac{\alpha_{tot}}{\Gamma \cdot G_0}\right) \qquad (15)$$

For α_{tot} = 23 cm^{-1}, J_{tr} = 490 A/cm^2 and $\Gamma \cdot G_0$ = 43 cm^{-1}; one obtains J_{tr} = 836 A/cm^2. This value is precise to about 0.7% of the directly measurement of the threshold current density.

The SE spectra obtained as described above for the various injection currents are shown in Fig. 5. Note that the SE spectrum amplitude logically increases with the injection current.

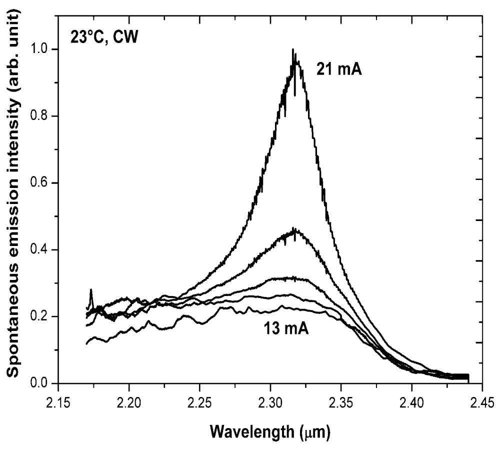


Fig. 5 Spontaneous emission spectra at injection currents of 13, 15, 17, 19 and 21 mA

To obtain information about the main recombination channel in the LD, we have analysed the relationship between the Integrated Spontaneous Emission Rate (*ISER*) over the whole wavelength range and the injection current. The Integrated Spontaneous Emission Rate is proportional to the square of the carry density [10]:

$$ISER = \int_0^{+\infty} r_{sp}(\lambda)\,d\lambda = BN^2 \qquad (16)$$

where B is the radiative recombination coefficient and N is the carrier density in the QWs. Furthermore, the total current density in the laser diode can be written as

$$J = \frac{q \cdot N_w \cdot L_w}{\eta_i}\left(AN + BN^2 + CN^3\right) \qquad (17)$$

where q is the charge of the electron, N_w, the number of quantum well, η_i, the injection efficiency accounting for the fraction of carriers which make it into the QW's, L_w, the thickness of a well, and A, B and C are the nonradiative monomolecular (Shockley & Read-Hall), radiative and Auger coefficients, respectively.

From (16) and (17), we can deduce that $(ISER)^{1/2} \propto N$ and $J \propto AN + BN^2 + CN^3$. Therefore, plotting J or I (current) as function of $(ISER)^{1/2}$ is equivalent to plotting J or I as function of N. On the plot cover, $I \propto N$ corresponds to the monomolecular recombination channel, $I \propto N^2$ corresponds to the radiative recombination channel and $I \propto N^3$ corresponds to the Auger recombination channel.

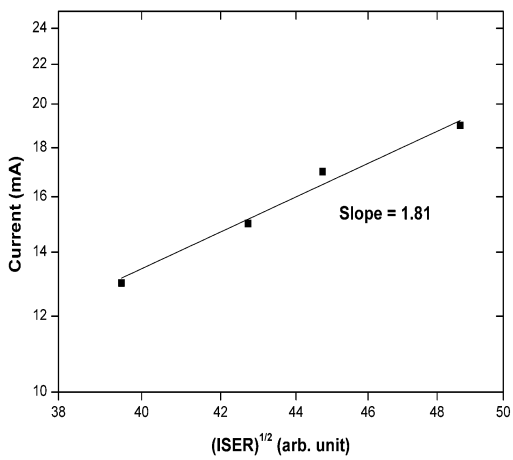


Fig.6. Variation of the current as a function of the square root of the integrated spontaneous emission rate in double logarithmic scale at 23°C

Fig. 6 shows the current plotted against the square root of ISER in double logarithmic scale. The variation of current appears linear on this log-log plot which means that it follows a power-law function. A value of 1.81 is found for the exponent implying that I = *cste* x $N^{1.81}$. The dependence $I \propto N^{1.81}$ confirms that the current in the GaInAsSb-AlGaAsSb diode laser emitting at 2.3 µm is dominated by radiative recombination [3, 20]. This gives further evidence for the quality of this laser heterostructure and confirms that the GaInAsSb/AlGaAsSb material system is well suited for developing mid-IR laser diodes.

5. CONCLUSION

We report measurements of amplified spontaneous emission from narrow ridge waveguide GaInAsSb-AlGaAsSb MQW laser operating in continuous wave and emitting near 2.3 µm at room temperature. Cassidy's method has been used to extract net modal gain. A convenient and effective method to extract the spontaneous emission of semiconductor lasers from the amplified spontaneous emission using single pass gain is proposed. Quantitative information about transparency current density and modal gain coefficient is obtained. The analysis of the integrated spontaneous emission rate shows an approximation between the injection current and the carrier density in the form of $I \propto N^{1.81}$. This indicates that the current is controlled by radiative recombination at 2,3 µm emission wavelength.

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