An efficient approach to characterizing and calculating carrier loss due to heating and barrier height variation in vertical-cavity surface-emitting lasers

Wu Jian(吴 坚)[a] and H. D. Summers[b]

[a] School of Physics and Nuclear Energy Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, China
[b] School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3YB, Wales, UK

(Received 30 March 2009; revised manuscript received 4 May 2009)

It is important to determine quantitatively the internal carrier loss arising from heating and barrier height variation in a vertical-cavity surface-emitting quantum well laser (VCSEL). However, it is generally difficult to realize this goal using purely theoretical formulas due to difficulty in deriving the parameters relating to the quantum well structure. In this paper, we describe an efficient approach to characterizing and calculating the carrier loss due to the heating and the barrier height change in the VCSEL. In the method, the thermal carrier loss mechanism is combined with gain measurement and calculation. The carrier loss is re-characterized in a calculable form by constructing the threshold current and gain detuning-related loss current using the measured gain data and then substituting them for the quantum well-related parameters in the formula. The result can be expressed as a product of an exponential weight factor linked to the barrier height change and the difference between the threshold current and gain detuning-related loss current. The gain variation at cavity frequency due to thermal carrier loss and gain detuning processes is measured by using an AlInGaAs–AlGaAs VCSEL structure. This work provides a useful approach to analysing threshold and loss properties of the VCSEL, particularly, gain offset design for high temperature operation of VCSELs.

Keywords: semiconductor laser, vertical cavity surface emitting laser, quantum well, thermal carrier loss

PACC: 4255P, 7320D

1. Introduction

Barrier height variation of a quantum well and self-heating in a vertical-cavity surface-emitting laser (VCSEL) are two important physical processes affecting device properties, such as quantum efficiency, threshold current, lasing power of devices, etc., as these processes are able to cause the carrier number for recombination or the cavity gain and loss to change. Therefore, the determination of the heating and the barrier height induced carrier loss is always necessary in VCSEL design in order to achieve optimal device properties. In theory, the carrier loss related to the temperature and barrier height of the well can be described with the carrier loss mechanism.[1,2] However, it is generally difficult to actually calculate the carrier loss by using the given theoretical formulas directly due to the difficulty in deriving detailed values of the parameters relating to the well structure. Although the studies on thermal properties of the VCSELs regarding gain variation and carrier loss have been mentioned in many articles so far,[3−12] most methods characterizing and describing the carrier loss related to the heating and the barrier height variation were based on complex, purely numerical modelling or rough experimental estimation, and thus failed to provide a convenient and efficient approach to calculating and assessing thermal carrier loss in the VCSEL.

Thus, here we describe an approach in which the heating and the barrier height change induced carrier loss in the VCSEL is able to be characterized and determined quantitatively and the use of the parameters difficult to determine in the calculation is avoided. In this method, the carrier loss mechanism of the quantum well is combined with gain measurement and calculation, and thus the carrier loss can be re-characterized in a calculable form by utilizing the threshold current and the gain-detuning related loss current, which are constructed by using the measured gain data, instead of the well structure-related parameters in the formula. This enables all parameters to be measurable in the carrier loss calculation. The gain measurement and calculation regarding thermal carrier loss and gain detuning processes in the VCSEL are carried out by using an AlInGaAs–AlGaAs VCSEL structure for the sample fabrication. This results

© 2010 Chinese Physical Society and IOP Publishing Ltd

in successful constructions of the threshold current and the gain detuning-related loss current in a separate form. The result provides a useful approach to analysing the threshold and loss properties of the VCSEL, particularly, gain offset determination by changing the band-gap of the quantum well.

2. Carrier loss mechanism

The carrier loss here is considered in two aspects. One is heating induced thermal carrier leakage arising from the well and the gain detuning effect. With temperature increasing within the VCSEL, electrons and holes are excited to higher energy states in the conduction and valence bands of the quantum well, respectively. The thermal carrier excitation due to heating changes the Fermi distribution of carriers in the well and finally leads to carrier leakage from the well into the cladding layers. This results in direct gain reduction over the whole spectral range for a fixed injection carrier density. The physical process of thermal carrier leakage can be understood by electron carrier distribution in the conduction band under thermal equilibrium. The hole carrier distribution in the valence band is in a similar form to the electron carrier's. The number of electrons with energy greater than the barrier height of the conduction band can be expressed as[1]

$$n_{\mathrm{b}} = \sum_i \left[\int_{E_{\mathrm{nt}}}^{\infty} g_{\mathrm{c}i} f_{\mathrm{c}} \left(E_i \right) \mathrm{d}E_i \right], \tag{1}$$

where E_{nt} is the energy of the well barrier, $g_{\mathrm{c}i}$ is the density of electron states per unit volume in the i-th sub-band higher than the barrier height, and $f_{\mathrm{c}}(E_i)$ is the Fermi function written as

$$f_{\mathrm{c}} \left(E_i \right) = \frac{1}{1 + \exp \left[(E_i - E_{\mathrm{fc}}) / k_{\mathrm{B}} T \right]} \tag{2}$$

with E_{fc} being the quasi-Fermi level in the conduction band. In the Boltzmann approximation, Eq. (1) can be expressed as

$$n_{\mathrm{b}} = g_{\mathrm{cn}} k_{\mathrm{B}} T^{3/2} \cdot \exp \left(- \frac{E_1}{k_{\mathrm{B}} T} \right), \tag{3}$$

where g_{cn} is the electron state density per unit volume in the sub-band with energy of E_{nt}, $E_1 = E_{\mathrm{nt}} - E_{\mathrm{fc}}$ denotes the energy greater than the quasi-Fermi level in the conduction band. Similar relations can be obtained for the holes in the valence band as well. Thus, the leakage carrier density, $J_{\mathrm{Le}}(T)$, can be described as follows, as it is proportional to the number of carriers with energies greater than the barrier height:

$$J_{\mathrm{Le}} \left(T \right) = G_{\mathrm{n}} T^{3/2} \cdot \exp \left(- \frac{E_1}{k_{\mathrm{B}} T} \right), \tag{4}$$

where G_{n} is a constant relating to the density of states of electron–hole pairs in the corresponding sub-bands with energy equivalent to the barrier height. Equation (4) characterizes the relationship between leakage carrier density and temperature or barrier height. However, it is difficult to calculate leakage carrier density in detail from this formula, as we do not know exactly the values of the parameters, G_{n} and E_1, which are related to the quantum well structure. Thus, to calculate the leakage carrier density efficiently, Eq. (4) should be altered by introducing measurable parameters.

The threshold current of a VCSEL device may consist of several items related to different physical processes, which can be written as

$$J_{\mathrm{th}} = J_{\mathrm{r}} + J_{\mathrm{nr}} + J_{\mathrm{Le}} + J_{\mathrm{gd}}, \tag{5}$$

where J_{r} and J_{nr} represent the radiative and the non-radiative current densities below the threshold, respectively. J_{Le} denotes the loss current density related to the thermal carrier leakage process in the well, and J_{gd} is a special loss current due to the gain detuning relative to the cavity mode in the VCSEL. Thus, the threshold current due to the effects of the gain detuning, radiative and non-radiative processes, excluding the thermal carrier leakage, can be written as

$$J'_{\mathrm{th}} = J_{\mathrm{r}} + J_{\mathrm{nr}} + J_{\mathrm{gd}}. \tag{6}$$

By substituting Eq. (6) into Eq. (5), the leakage current density, J_{Le}, can be expressed as

$$J_{\mathrm{Le}} = J_{\mathrm{th}} - J'_{\mathrm{th}}. \tag{7}$$

Since the current densities determined by the radiative and the non-radiative processes are generally very low below the threshold, the threshold current density excluding the thermal carrier leakage influence is actually predominated by the gain detuning effect when the device is heated up, particularly when the device operates at high temperatures. Thus, Eq. (7) may be regarded approximately as

$$J_{\mathrm{Le}} \approx J_{\mathrm{th}} - J_{\mathrm{gd}}. \tag{8}$$

In Eq. (8), the threshold current J_{th} involving both thermal carrier loss and gain detuning effects can be derived by either direct threshold current measurement or construction using gain data. The gain

detuning-related loss current, $J_{\rm gd}$ can be constructed with gain data. Equation (8) gives an alternative and calculable form for the thermal leakage current characterization, in which all currents are available from gain measurement and calculation compared with Eq. (4).

The other factor affecting the carrier loss is barrier height variation of the well, which usually occurs when the band-gap of the well is changed, for example, the use of gain offset in VCSEL design. Thus, the overall leakage carrier density involving the barrier height variation can be expressed theoretically as

$$J_{\rm L} = G_{\rm n} T^{3/2} \cdot \exp\left(-\frac{E_1 - \Delta E}{k_{\rm B} T}\right), \tag{9}$$

where ΔE is the variation of barrier height. Equation (9) can also be re-written as a product of the thermal carrier excitation-induced leakage current density $J_{\rm Le}(T)$ and an exponential weight factor related to the barrier height alteration, which is given by

$$J_{\rm L} = J_{\rm Le} \exp\left(\frac{\Delta E}{k_{\rm B} T}\right). \tag{10}$$

Thus, Eq. (10) establishes the relationship between total carrier loss and thermal carrier leakage or barrier height variation. By substituting Eq. (8) into Eq. (10), the total carrier loss can be expressed as

$$J_{\rm L} = (J_{\rm th} - J_{\rm gd}) \exp\left(\frac{\Delta E}{k_{\rm B} T}\right). \tag{11}$$

Equation (11) provides a simple, efficient analytical form for the actual calculation and assessment of the carrier loss induced by both the heating and the barrier height variation, as all parameters in the equation are available.

3. Determination of gain detuning-related loss current

The gain detuning-related loss current can be determined by gain measurement and calculation. The method and the device structure used for the gain measurement of the VCSEL here are the same as those mentioned in the literature.[13,14] The samples were fabricated using the AlInGaAs–AlGaAs VCSEL structure. The active region of the VCSEL was composed of three 7.5 nm $(Al_{0.09}Ga_{0.91})_{0.94}In_{0.06}As$ quantum wells. Each well was sandwiched by $Al_{0.3}Ga_{0.7}As$ layers. The distributed Bragg reflectors (DBR) were composed of 22 and 32 AlAs/AlGaAs half-wavelength pairs for top and bottom mirrors, respectively. The cavity wavelength varied from 800 to 814 nm for different samples. One of the measured gains as a function of temperature for a fixed injection current density of 660 A·cm^{-2} is shown in Fig. 1, in which the cavity wavelength is 812 nm at room temperature.

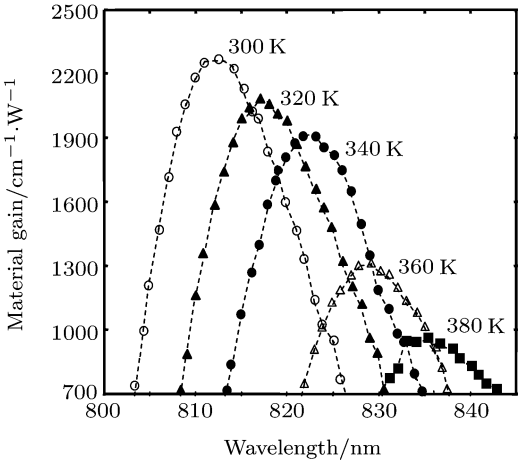


Fig. 1. Material gain of an AlInGaAs–AlGaAs VCSEL as a function of temperature for a fixed injection current density of 660 A·cm^{-2}.

Obviously, the gain variation at the cavity frequency consists of two parts. One is from the thermal carrier loss that directly causes gain peak reduction. The other is due to the gain detuning effect that leads to the gain change at the cavity frequency or wavelength. This provides a chance to derive thermal detuning-induced gain variation at the cavity frequency independently from thermal carrier loss influence by moving the gain curve obtained at room temperature at the same thermal detuning rate as what is actually

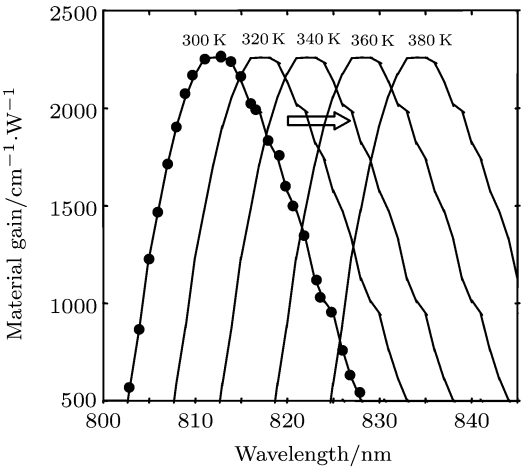


Fig. 2. Gain detuning relative to the cavity wavelength of 812 nm from an AlInGaAs–AlGaAs VCSEL with an injected current density of 660 A·cm^{-2}.

measured under different temperatures, which can be obtained from Fig. 1. This yields the result in Fig. 2 for the injected current density of 660 A·cm^{-2} and cavity wavelength of 812 nm at room temperature.

The threshold currents at different temperatures can be constructed by comparing the measured gain data at the cavity frequency with the threshold gain value that is calculated as a calibration for the threshold current determination. The threshold gain is determined by the self-consistency condition of the VCSEL and is given by[1]

$$g_{\rm th} = \frac{1}{\Gamma_{\rm vertical}} \left[\alpha_i - \frac{1}{2L_{\rm eff}} \ln (R_1 R_2) \right], \qquad (12)$$

where $\alpha_{\rm i}$ denotes the internal loss of the materials, which can be determined by the measured modal gain. $L_{\rm eff}$ is the effective length of the cavity with multiple active layer structure, which is $\lambda/2$ for the cavity wavelength of 812 nm at room temperature in this paper. R_1 and R_2 represent the power reflectivity of top and bottom DBR mirrors, respectively. The internal loss, $\alpha_{\rm i}$, is -15 cm^{-1} from the measured gain data. The threshold gain is 1200 cm^{-1} for the given device parameters. The gain detuning-related loss currents are constructed from three samples with cavity wavelengths of 804, 812 and 814 nm, respectively. The results are shown in Fig. 3. Dash curves denote the gain detuning-related loss currents. As a contrast, the total threshold currents (solid curves) are plotted as well.

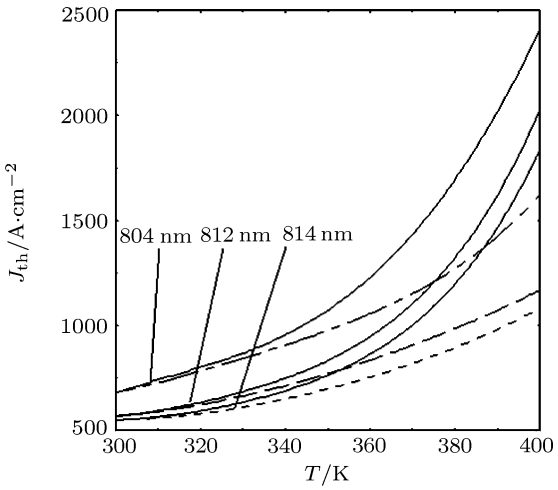


Fig. 3. Constructed total threshold currents (solid curves) and gain detuning-related loss currents (dash curves) using AlInGaAs–AlGaAs VCSELs.

By combining the constructed threshold currents and gain detuning-related loss currents with Eq. (11), the loss current density due to both the heating and the barrier height variation can be calculated efficiently. The temperature-dependent loss current density arising from a barrier height variation of $\Delta E = 1.88\times10^{-2}$ eV by using the above approach is shown in Fig. 4 (dash curve). The cavity wavelength is 812 nm at room temperature. The barrier height change of $\Delta E = 1.88 \times 10^{-2}$ eV may be from altering the bandgap of the well, which corresponds to a 10 nm gain offset. As a contrast, the leakage-induced loss current density $J_{\rm Le}$ without barrier height alteration (solid curve) is plotted as well. It is clearly shown that the carrier loss is sensitive to the barrier height variation.

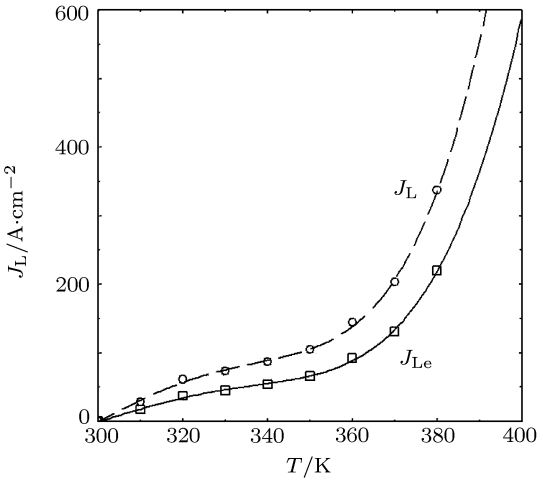


Fig. 4. Temperature-dependent carrier losses with barrier height change of $\Delta E = 1.89 \times 10^{-2}$ eV (dash curve) and without barrier height alteration (solid curve).

4. Conclusion

Since it is generally difficult to characterize and calculate quantitatively internal carrier loss arising from heating and barrier height variation in a vertical-cavity surface-emitting quantum well laser (VCSEL) by purely theoretical formulas due to difficulty in deriving theoretical parameters relating to quantum well structure, we describe an efficient approach to characterizing and determining the carrier loss related to the heating and the barrier height variation of the well by combining the thermal carrier loss mechanism with gain measurement and calculation.

In the carrier loss mechanism, the carrier loss due to the heating and the barrier height variation is re-characterized in a convenient analytical form by utilizing the threshold current and gain detuning-related loss current instead of parameters which are difficult to determine in the formula. The result can be expressed as a product of an exponential weight factor

related to the barrier height variation and the difference between the threshold current and gain detuning-related loss current. This enables all parameters to be measurable in the calculation.

The threshold current and the gain detuning-related loss current can be constructed by gain measurement and calculation. This makes the above method of calculating the carrier loss from the heating and the barrier height change feasible. The devices used for the gain measurement are based on an AlInGaAs–AlGaAs VCSEL structure with cavity wavelength ranging from 804 to 814 nm. The temperature-dependent threshold current and the gain detuning-related loss current are constructed successfully by comparing the measured gains at the cavity frequency with the threshold gain value. This approach provides a useful method of analysing the threshold and loss properties of the VCSEL, particularly the gain offset design for high temperature operation of the VCSELs.

References

[1] Agrawal G P and Dutta N K 1993 *Semiconductor Lasers* (New York: Van Nostrand Reinhold) p426

[2] Coldren L A and Corzine S W 1995 *Diode Lasers and Photonic Integrated Circuits* (New York: John Wiley & Sons) p421

[3] Knowles G, Sweeney S J and Sale T 2001 *IEE Proc. Optoelectron.* **148** 55

[4] Catchmark J M, Morgan R A, Asom M T, Guth G D, Focht M W, Mullally T and Christodoulides D N 1994 *Electron. Lett.* **30** 2136

[5] Piprek J, Akulova Y A, Babic D I, Coldren L A and Bowers J E 1998 *Appl. Phys. Lett.* **72** 1814

[6] Young D B, Scott J W, Peters F H, Peters M G, Majewski M L, Thibeault B J, Corzine S W and Coldren L A 1993 *IEEE J. Quant. Electron.* **29** 2013

[7] Mogg S, Chitica N, Christiansson U, Schatz R, Sundgren P, Asplund C and Hammar M 2004 *IEEE J. Quant. Electron.* **40** 453

[8] Shoji H, Otsubo K, Matsuda M and Ishikawa H 1994 *Electron. Lett.* **30** 409

[9] Morgan R A, Hibbs-Brenner M K, Marta T M, Walterson R A, Bounnak S, Kalweit E L and Lehman J A 1995 *IEEE Photon. Technol. Lett.* **7** 441

[10] Osinski M 1995 *SPIE* **2398** 42

[11] McMahon C H, Bae J W, Menoni C S, Patel D, Temkin H, Brusenbach P and Leibenguth R 1995 *Appl. Phys. Lett.* **66** 2171

[12] Lu B, Zhou P, Cheng J, Malloy K J and Zolper J C 1994 *Appl. Phys. Lett.* **65** 1337

[13] Summers H D and Wu J 2001 *IEE Proc. Optoelectron.* **148** 261

[14] Wu J, Xiao W and Lu Y 2007 *IET Optoelectron.* **1** 206