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Influence of Temperature on Steady-State Performance of VCSEL

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Abstract

During the recent years, vertical cavity surface emitting laser (VCSEL) is being widely used as one of the most promising optoelectronic devices. It has released the bottlenecks of electrical interconnects in the complex VLSI and ULSI circuits, such as speed, packaging, fan-out and power dissipation. But still it has a major limitation, because it is easily influenced by the temperature and it has a tendency of generating heat inside the laser cavity. So the study on this topic has become essential. The steady-state characteristics, including lasing frequency and threshold current of VCSEL under the influence of temperature are analyzed. Both simple and comprehensive methods to calculate heat distribution inside the laser cavity are studied in this article.

Keywords- *VCSEL; Quantum Well; Lasing Wavelength; Threshold Current; Gain Spectrum*

1. Introduction

VCSEL has attracted considerable interest since the mid-1990s because of its single longitudinal-mode operation, circular output beams with low divergence, the possibility of monolithic two-dimensional integration and the compatibility with on-wafer probe testing. Despite these advantages, VCSEL still exhibits a number of undesirable features such as the excitation of higher-order transverse modes and the undetermined polarization properties [1]. In fact, the most widely recognized limitation on the performance of VCSEL is the generation of heat inside the laser cavity [2]. Self-heating in VCSEL can be attributed to the excessive heat source and the accumulation of heat inside the laser cavity. Excessive heat source is due to the high series resistance of the doped semiconductor distributed Bragg reflectors (DBRs), which is much greater than that of facet emitting lasers [3]. The temperature at the active layer, T_{active} can be estimated by $T_{active} = T_{HS} + R_T IV$, where T_{HS} is the heat sink temperature, R_T is the total thermal resistance and IV is the equivalent electrical power dissipated inside the VCSEL. Hence, serious heat accumulation inside the laser cavity is unavoidable because of high thermal resistance and injection current density. The substantial increase in temperature causes the increase in threshold current density, the reduction of output optical power and the shift of resonant frequency to the longer wavelength. As a result, the influence of thermal effect on device performance is more pronounced in VCSEL than in facet emitting lasers. Furthermore, thermal problems are even more pressing in VCSEL arrays where long-range thermal crosstalk is of great concern [4]. Therefore, the challenge for designing VCSEL operating at CW condition is to improve the heat dissipation efficiency, reduce the threshold current density and increase the output optical power.

In this article, the steady-state performance of VCSEL under the influence of self-heating is reviewed. The dependence of lasing wavelength as well as threshold current on the temperature of laser cavity is described.

2. VCSEL Technology

VCSELs were first invented in the mid-1980's. Very soon, VCSELs gained a reputation as a superior technology for short reach applications such as fiber-channel, Ethernet and intra-systems links. Then, within the first two years of commercial availability, VCSELs became the technology of choice for local area networks, effectively displacing edge-emitter lasers. This success was mainly due to the VCSEL's lower manufacturing costs and higher reliability compared to edge-emitters.

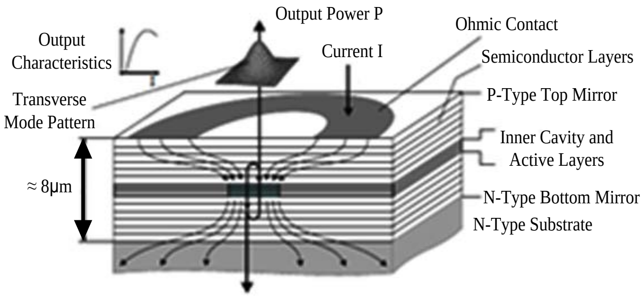

Figure 1. Schematic layer structure and operation principle of VCSEL

Fig. 1 illustrates the typical layout of a VCSEL [5, 6]. The inner cavity containing the amplifying layers is surrounded by electrically conductive layer stacks that form the laser mirrors which provide optical feedback. VCSELs designed for emission wavelengths in the 850 nm to 980nm spectral range require about 8µm of epitaxially grown material, whereas the active region is composed of just a few quantum wells (QWs) with some ten nm thickness. In the most simple device layouts, electric current is injected from ohmic contacts on the top epitaxial side and the backside of the substrate. Several methods have been successfully employed to achieve current confinement to a predefined active area.

The active diameter of the VCSEL can be reduced to just a few micrometers in order to obtain lowest threshold currents in the sub-100µA range [7], but can also exceed 100µm to get high output powers beyond 100mW[8, 9].

3. Influence on Lasing Wavelength

Before A typical VCSEL structure consists of two DBRs separated by a spacer layer, which incorporates an active layer [10]. If the lasing wavelength of the VCSEL is designed to be λ_R, the thickness of the spacer layer and all layers of the two DBRs should be selected as λ_R and $\lambda_R/4$, respectively. In this case, the peak of the standing wave intensity is located at the position of the active layer so that λ_R can be expressed as $\lambda_R = n_{spacer} h_{spacer}$, where n_{spacer} is assumed to be the effective refractive index of the spacer layer, including the active layer and h_{spacer} is the corresponding physical thickness.

The refractive index and thickness of all layers of the laser cavity are temperature-dependent. Therefore, the exact value of λ_R can be calculated only by the numerical technique with the change of refractive index Δn and thickness $\Delta h$of all layers with temperature included in the calculation. The variation of Δn and Δhcan be approximated by,

$$\Delta n \cong \frac{\partial n}{\partial T}\Delta T + \frac{\partial n}{\partial \lambda}\Delta\lambda_R$$

$$\Delta h \cong \lambda_R \frac{\partial h}{\partial T}\Delta T$$

where, ΔT and $\Delta\lambda_R$ are the change in temperature and resonant wavelength, respectively. The partial derivatives $\partial n/\partial T$ and $\partial n/\partial \lambda$ are to be evaluated at constant wavelength and temperature, respectively, for the calculation of the change in refractive index. The remaining partial derivative, $\partial h/\partial T$, is the linear thermal expansion coefficient. The thermal dispersion of the DBRs and spacer layer are matched and are given by [11].

$$\frac{1}{n_{spacer}}\frac{\partial n_{spacer}}{\partial T} = \frac{1}{n_L h_L + n_H h_H}\left[h_L\frac{\partial n_L}{\partial T} + h_H\frac{\partial n_H}{\partial T}\right]$$

Where n_L (n_H) is the refractive index and h_L (h_H) is the thickness of layers. The subscripts L and H represent the low and high refractive indices of the layers of DBRs, respectively. The rate of change of λ_R with temperature can be determined from the temperature sensitivity of the refractive index and thermal expansion of the spacer layer,

$$\frac{\partial\lambda_R}{\partial T} = \frac{\lambda_R}{n_g}\left[\frac{\partial n_{spacer}}{\partial T} + n_{spacer}\frac{\partial h_{spacer}}{\partial T}\right]$$

Where n_g is the group refractive index of the spacer layer and is expressed as,

$$n_g = n_{spacer} - \lambda_R\frac{\partial n}{\partial T}$$

Figure 2 shows the measured lasing wavelength and threshold current of gain-guided VCSEL under the influence of temperature [12]. The laser is designed to operate at 1.54μm wavelength at room temperature. It is found that for the VCSEL, $\partial\lambda_R/\partial T$ is about 0.1 nm/K. Substituting the parameters given in Table 1 into the previous equations, it can be shown that the calculated $\partial\lambda_R/\partial T$ is close to that given from the measurement. This indicates that the thermal dispersion matching condition given is satisfied and the detuning of λ_R can be estimated by the change of refractive index inside the spacer layer.

In fact, it is shown experimentally that the value of $\partial\lambda_R/\partial T$ for VCSEL, firstly, with AlGaAs/GaAs mirrors plus $Al_{0.4}Ga_{0.6}As$ spacer layer operating at 0.95μm wavelength [13] and secondly, with AlGaAs/GaAs mirrors plus GaAs spacer layer operating at 1.25μm wavelength [14] are found to be 0.084 nm/K and 0.088 nm/K, respectively, which are matched with the calculated values obtained using the parameters given in Table 1.

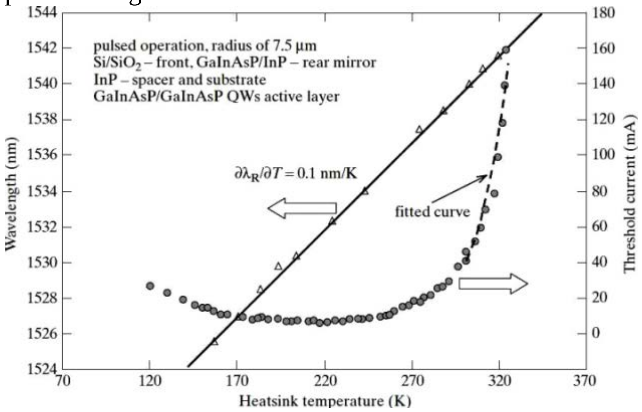

Figure 2. Lasing wavelength and threshold current (under pulsed operation) as a function of temperature for a 15μm diameter VCSEL

4. Influence on Threshold Current

Figure 2 shows that the threshold current I_{th} convexes downward and reaches minimum at a temperature around 220 K. This profile of I_{th} is, in fact, atypical characteristic of VCSEL, which is different from those of facet emitting lasers. For facet emitting lasers, I_{th} decreases monotonically with the reduction of temperature. In VCSEL, the variation of temperature leads to an offset between λ_p and λ_R as $\partial\lambda_R/\partial T < \partial\lambda_p/\partial T$.

Figure 3 compares the variation of λ_p and λ_R with temperature and the corresponding temperature dependence of optical gain spectra is also inserted in the Figure [15]. It is observed that near 270 K, $\lambda_p = \lambda_R$. For temperatures higher than 270 K, optical gain reduces monotonically at λ_R so that the corresponding threshold current is increased. On the other hand, for temperatures between 170 K and 270 K, the optical gain at λ_R as well as the threshold current remains unchanged. Further reduction of temperature from 170 K reduces optical gain at λ_R so that the threshold current is increased. Hence, the profile of I_{th} exhibits a downward convex over this range of temperature. It is observed from Fig. 2 that the minimum value of I_{th} occurs near 220 K but not at 270 K, which implies that other temperature-dependent loss mechanisms influence the overall cavity loss. Nevertheless, the condition of $\lambda_p = \lambda_R$ gives a close estimation on the minimum value of I_{th}. It is noted that VCSEL under the condition of $\lambda_p = \lambda_R$ can produce a reasonably low threshold current, but the required operating temperature may not be appropriate for normal application.

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Table 1 VCSEL Temperature-Lasing Wavelength Profile

Material	$\partial h/\partial T$ (10^{-6}°C^{-1})	$\partial n/\partial T$ ($\times 10^{-4}$ K^{-1})	n (RT)	n_g (RT)	κ (W cm^{-1} K^{-1})
GaAs	6.4 – 6.9	~4 at 1.25µm	~3.4 at 1.25µm	4.4 at 1.25µm	0.44
$Al_xGa_{1-x}As$	6.4 – 1.2x	~4 at 0.95µm	~3.5 at 0.95µm	4.3 at 0.95µm	0.44/(1+12.7x–13.22x^2)
InP	4.59	~3 at 1.5µm	~3.6 at 1.5µm	4.6 at 1.5µm	0.68
$In_{1-x}Ga_xAs_yP_{1-y}$	4.56 + 1.18y	~3 at 1.3µm	~3.6 at 1.5µm	4.6 at 1.55µm	~0.382

In order to optimize I_{th} at a desired operating temperature, suitable selection of gain offset wavelength (i.e., $\lambda_p - \lambda_R$) is required, which can be obtained by varying the design of DBRs for different λ_R.

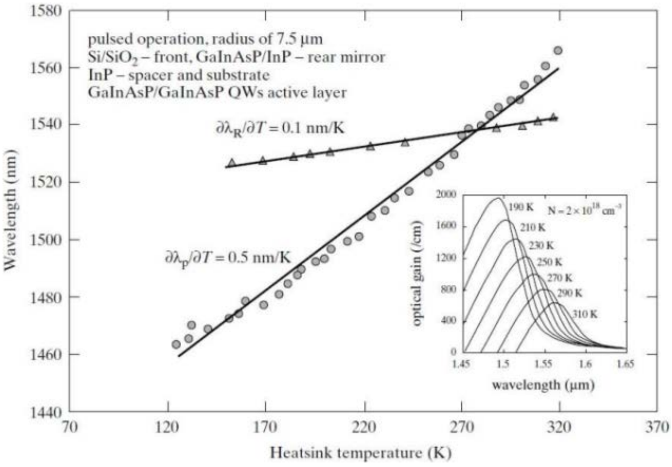

Figure 3. Variation of cavity mode λ_R and λ_p optical gain with temperature.

The inset diagram gives the QW's gain spectrum at different ambient temperatures showing the thermal shift of the peak gain wavelength λp as well as of the magnitude of peak gain.

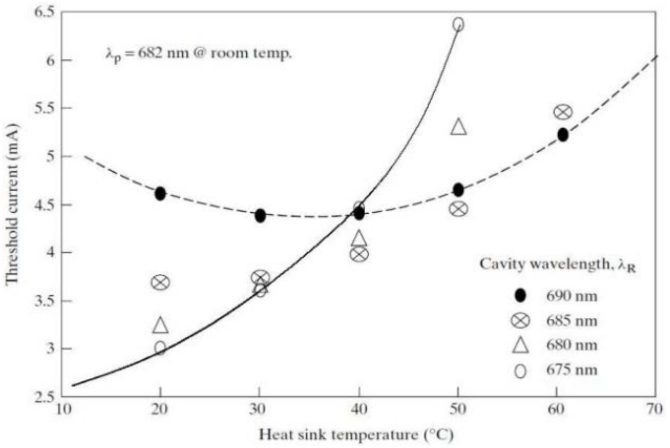

Figure 4. Threshold current as a function of heat sink temperature for various 20µm diameter VCSEL; the wavelength designation refers to the VCSEL emission wavelength as sub threshold.

Analysis of AlGaInP-based 670 nm–690 nm VCSEL [16] shows that suitable selection of gain offset wavelength can provide a minimum threshold current as well as a maximum output power over a wide temperature range. The VCSEL under investigation have planar gain-guided structure, which are fabricated in a front emitting geometry with proton implantation to define device diameters and to channel current into the active region. The front and rear DBRs are composed of $Al_{0.5}Ga_{0.5}As$ and AlAs quarter-wave layers sandwiched between the $In_{0.56}Ga_{0.44}P$ QWs with barriers and cladding layers of $(Al_{0.5}Ga_{0.5})_{0.5}In_{0.5}P$ on each side of the wells. Figure 4 shows the threshold current for the four 20 µm diameter devices as a function of heat sink temperature. The devices have four resonant wavelengths λ_R, which varies from 675 nm to 690 nm and the peak gain wavelength λ_p of the QW active layer is 688 nm, where both λ_R and λ_p are measured at room temperature. It is observed that the threshold current of VCSEL with λ_R equal to 675 nm, 680 nm and 685 nm increases monotonically with temperature. In contrast, the threshold current of VCSEL with λ_R= 690nm initially decreases with temperature but increases with increase of temperature beyond 30°C, which is the heat sink temperature of an optimal gain peak/cavity mode overlap. Furthermore, it is noted that the threshold current of the 690 nm lasers over the temperature range of 20°C – 50°C is relatively constant when compared with the other lasers. Hence, the required gain wavelength offset for VCSEL with uniform threshold current over an operating temperature range is $\lambda_p - \lambda_R < 0$ at room temperature.

5. Discussion and Result

Figure 2 shows that for VCSEL, $\partial\lambda_R/\partial T$ is about 0.1 nm/K. Substituting the parameters given in Table 1 into the equations shown in that section, it can be shown that the calculated $\partial\lambda_R/\partial T$ is close to that given from the measurement. This indicates that the thermal dispersion matching condition given is satisfied and the detuning of λ_R can be estimated by the change of refractive index inside the spacer layer. For VCSEL, it is shown that the value of $\partial\lambda_R/\partial T$is around 0.085 nm, which is almost similar with the calculated values obtained using the parameters in Table 1. From Figure 2, it is also observed that, I_{th}convexes downward and has a minimum value around 190K to 240K. But for facet emitting lasers, I_{th} decreases with the reduction of temperature continuously.

From Figure 3, it is observed that, when the temperature is between 170K and 270K, the optical gain and the threshold current remain unchanged. Thus in this range, I_{th} exhibits a downward convex, where the minimum value is near the temperature 270K. But in Figure 2, the minimum value of I_{th} occurs near 220K, which indicates that some other temperature-dependent loss mechanisms influence the overall cavity loss. VCSEL under the condition of $\lambda_P = \lambda_R$ can produce a reasonably low I_{th}, but the required operating temperature may not be appropriate for normal application.

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6. Conclusion

Thermal runaway of the embedded VCSEL is the critical concern due to the reliable operation of VCSEL for a long time. In this letter change in lasing wavelength and threshold current of VCSEL is described due to the change of temperature. From the figures, these important factors of this device can be predicted. Values for different temperature are compared and it is clear that the observed result is very close to the calculated result. Simple thermal model and quasi-three-dimensional thermal model are the next important subjects to be studied.

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