Cross-plane thermal diffusivity measurement of an operating vertical cavity surface emitting laser using thermoreflectance

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Cross-plane thermal diffusivity measurement of an operating vertical cavity surface emitting laser using thermoreflectance

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Cross-plane thermal diffusivity of a GaAs/AlGaAs-based vertical cavity surface emitting laser (VCSEL) is measured under operating conditions and active heat sinking using a thermoreflectance technique. Perpendicular thermal diffusivity is determined from the measurements of phase difference between the heating source and the temperature as a function of temperature modulation frequency. The value of $(1.22 \pm 0.23) \times 10^{-6} \text{m}^2/\text{s}$ is obtained for thermal diffusivity, which is of the same order as previous values obtained on unbiased VCSEL structures. This is 10–14 times smaller than the corresponding bulk value. The reduction is attributed to the increase in phonon-boundary scattering in the multilayer structure of the VCSEL.

INTRODUCTION

Vertical cavity surface emitting lasers (VCSELs) are semiconductor laser diodes with a broad range of applications especially in fiber optics telecommunication. Temperature is known to affect the VCSEL performance in various ways such as local gain compression, shifts in the threshold current, restrictions of the output optical power, self-focusing due to thermal lensing, and polarization switching. A better understanding of how the VCSEL’s thermophysical properties affect its performance under operating conditions is crucial in improving the device design, packaging and thermal management.

Previous studies of temperature measurements and profiling of the VCSELs under operating conditions include spontaneous electroluminescence wavelength shift ($\mu$-EL), scanning thermal microscopy (SThM), and thermoreflectance microscopy. $\mu$-EL reveals a spatially resolved temperature distribution of the VCSEL with a resolution of about 1-2 $\mu$m. SThM, which is based on combining an atomic force microscope (AFM) probe with a microthermocouple, has been used on a cross-sectioned VCSEL. Because the light is emitted perpendicular to the surface of the VCSEL, the thermocouple cannot be used on the surface of the lasing aperture where it can absorb the emitted light and result in an erroneous temperature reading. High resolution, noncontact thermoreflectance microscopy has yielded thermal images of the VCSEL surface. These images have revealed that small aperture VCSELs show higher thermal resistance and more pronounced thermal lensing.

A previous study of thermophysical properties of a VCSEL structure was carried out by Chen et al. on an unbiased GaAs/AlGaAs multilayer structure. In that study, both in-plane and cross-plane thermal diffusivities of the structure were measured using an experimental method similar to ac-calorimetric techniques. The results showed an anisotropy in thermal diffusivity with a smaller cross-plane than in-plane diffusivity. Both of these values were found to be five to seven times smaller than the values in the corresponding bulk materials. This reduction in semiconductor multilayer nanostructures compared to the bulk is attributed to the increase in scattering of the heat carriers at the layer boundaries.

In a more recent work, an effective thermal diffusivity of a multilayered VCSEL array structure using thermoreflectance microscopy was measured to be $1.47 \times 10^{-5} \text{m}^2/\text{s}$. Frequency domain thermoreflectance has also been used to thermally characterize thin metal films on low thermal diffusivity substrates.

In this communication, we report on the results of the cross-plane thermal diffusivity measurement in a biased VCSEL under operating conditions using the thermoreflectance technique. The extraction of this parameter does not require a prior knowledge or measurement of the thermoreflectance coefficient, which greatly simplifies the experimental technique.

The VCSEL under test was a commercial Thorlabs multimode, oxide confined laser with a lasing peak at 850 nm. The laser consisted of 27 and 37 pairs of GaAs/AlGaAs in the top and bottom DBR mirrors, respectively, which resulted in a 3.5 $\mu$m thick top DBR mirror and a 4.8 $\mu$m thick bottom DBR mirror. The threshold current of the VCSEL was measured to be 1.6 mA. An estimate of the thermal resistance ($R_{th}$) was obtained using the shift in the lasing wavelength with a value of $R_{th} = 0.9^o \text{C}/\text{mW}$, which is consistent with previously measured thermal resistance of a multimode VCSEL.

The VCSEL was mounted on a copper/aluminum stage, and the stage temperature was actively controlled at 25 $^o$C using a thermoelectric cooler. In all the following experiments, it was assumed that the majority of heat was created in the active region of the VCSEL between the top and bottom mirrors. The reflectivity variations were then measured at the surface of the top DBR mirror using the thermoreflectance technique.

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Thermoreflectance is based on measuring the change in surface reflectivity as a function of change in temperature. To the first order, the relative change in reflectivity ($\Delta R / R$) and the temperature change ($\Delta T$) are linearly related such that $\Delta R / R = \kappa \Delta T$. Here, $\kappa$ is the thermoreflectance coefficient that depends on the wavelength of the illuminating light and the sample material. It is necessary to determine $\kappa$ through an independent calibration experiment for translating the change of reflectivity signal to a temperature scale.

The schematic of the experimental setup is shown in Fig. 1. The illuminating light source was a 532 nm diode laser module that was polarized after passing through a polarizing beam splitter cube and a quarter-wave plate. The light was then focused on the VCSEL aperture using a 20x microscope objective, and the back reflected light was detected by a Si photodetector. To block the VCSEL laser radiation to reach the detector, a green laser-line filter along with spatial filters were placed in front of the photodetector. The temperature of the VCSEL was changed by a square wave modulation of the bias current using a function generator. Because the values of $\kappa$ are usually small (of the order of $10^{-4}$ or $10^{-5}$ K$^{-1}$ for semiconductors), it is necessary to use a lock-in amplifier with the modulation signal at its reference input to extract the thermal signal from noise. In our experiment, the signal was locked to the first harmonic of the square wave.

Using a lock-in amplifier enables us to measure not only the reflectance signal proportional to the temperature change, but also the phase difference between the heating source and the temperature. These two parameters (signal amplitude and the phase) were measured as a function of heating wave frequency. Figure 2 shows a plot of normalized thermal signal as a function of square wave frequency as a function of square wave frequency. The data are normalized to the value at lowest frequency of 100 Hz.

To measure the cross-plane thermal diffusivity ($a_{\perp}$) of the VCSEL, the phase difference between the heating source and the temperature was measured as a function of frequency. Because the thermal diffusion times in the perpendicular direction are of the order of microseconds, these measurements should be carried out at higher frequencies. The chosen range of frequencies for this part of the experiment is 50-100 kHz as shown in Fig. 3.

As a first approach to extract $a_{\perp}$, a simple one dimensional model assuming a local heat source at a known depth $h$ is used. The solution to the one-dimensional heat conduction equation perpendicular to the VCSEL yields a relation for the phase difference $\phi$ as a function of frequency $f$, assuming that the effects of heat transfer to the ambient due to convection are negligible compared to perpendicular thermal conductivity of the VCSEL structure. The phase difference is then given by

$$a_{\perp} = (1.22 \pm 0.23) \times 10^{-6} \text{ m}^2/\text{s}$$

FIG. 1. (Color online) Schematic of the experimental setup for measuring cross-plane thermal diffusivity of the VCSEL.

FIG. 2. Plot of normalized thermal signal as a function of square wave frequency. The data are normalized to the value at lowest frequency of 100 Hz.

FIG. 3. (Color online) Plot of phase difference between the heating source and the temperature as a function of square wave frequency. The solid curve is a theoretical fit using Eq (1). The error bars are about the same order as the size of the symbols. A value of $a_{\perp} = (1.22 \pm 0.23) \times 10^{-6} \text{ m}^2/\text{s}$ for cross-plane thermal diffusivity of the VCSEL was derived from the fit parameters.
TABLE I. Cross-plane thermal diffusivity of the VCSEL and GaAs/AlGaAs bulk as measured in this work and in Ref. 9.

<table>
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<tr>
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<th>Chen et al.(^b)</th>
<th>Present work</th>
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<tr>
<td>Bulk GaAs/AlGaAs</td>
<td>12.6 ± 0.3</td>
<td>1.22 ± 0.23</td>
</tr>
<tr>
<td></td>
<td>(^a)Reference 9.</td>
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\(a_{\perp} (\times 10^{-6} \text{ m}^2/\text{s})\)

\[
\phi(f) - \phi(f_0) = \frac{1}{2} (y - y_0) + \tan^{-1} \left\{ \frac{e^{-\gamma y_0} \sin(y_0)}{1 - e^{-\gamma} \cos(y_0)} \right\} \]

where \(y = 2h \sqrt{\sigma f / a_{\perp}}\), \(y_0 = 2h \sqrt{\sigma f_0 / a_{\perp}}\), \(f_0 = 50 \text{ kHz}\), and \(h = 3.5 \mu\text{m}\) is the approximate thickness of the top DBR mirror, which is also the distance between the heat source at the active region to the surface of the VCSEL where the temperature is measured. The value of thermal diffusivity is provided by the manufacturer (Thorlabs). Phase measurements of Fig. 3 are fitted using Eq. (1), keeping \(a_{\perp}\) as the fit parameter. A value of \((1.22 \pm 0.23) \times 10^{-6} \text{ m}^2/\text{s}\) is derived from the best curve fit. The maximum uncertainty in the value of diffusivity is calculated following the standard method explained in Ref. 9 by taking the relative uncertainty in thickness \(h\) to be 3%. An increase in \(h\) would result in an increase in the value of cross-plane diffusivity. For example only considering a 3% variation in \(h\) would result in approximately 6% change in the value of \(a_{\perp}\).

The value of thermal diffusivity is in very good agreement with the measurements of Chen et al. using an external heat source on an unbiased VCSEL structure with a 29.5-\(\mu\text{m}\) active region with three InGaAs quantum wells with a total thickness of 7.21 \(\mu\text{m}\) after etching. Table I shows a comparison between our measured value and the value from Ref. 9 in addition to the measured bulk thermal diffusivity of GaAs and AlGaAs reported in Ref. 9.

The discrepancy between the thermal diffusivity values measured in this work and by Chen et al. can be due to the fact that the two VCSEL structures are different in number of layers, thickness, and doping levels. In addition, in our experiment, the VCSEL was under operating conditions and actively heat sunked, whereas in the work done by Chen et al., the unbiased VCSEL structure was optically heated on one side and the temperature was measured on the back side.

Comparison of our measured thermal diffusivity value with the bulk values of the corresponding semiconductor materials reveals a reduction of about 10–14 times. This reduction can be attributed to the increase in phonon-boundary scattering in the multilayer structure of the VCSEL compared to the bulk. The acoustic phonons that act as heat carriers at room temperature in the semiconductor have a mean free path of about 1–100 nm, which is of the same order as the multilayer length scales. This can cause changes in the phonon dispersion relation and a reduction in thermal conductivity.

It should be noted that the one-dimensional heat conduction model used in this paper is only a first approach to the problem of extracting cross-plane thermal diffusivity. An improvement on the model should take into account the effects of both localized Joule heating and distributed optical absorption through different layers of the top DBR mirror of the VCSEL. This approach could result in a more reliable modeling of the thermal phase on the surface.

In summary, we measured cross-plane thermal diffusivity of a VCSEL under operating conditions using thermoreflectance technique and a simple first approach heat conduction model. The measured value of \((1.22 \pm 0.23) \times 10^{-6} \text{ m}^2/\text{s}\) is in good agreement with the previous work and shows the expected reduction compared to the bulk value because of the increase in phonon-boundary scattering. Future work will involve measuring the cross-plane thermal diffusivity from thermal images using CVD-based thermoreflectance microscopy and measuring the in-plane thermal diffusivity and anisotropy in thermophysical properties of the VCSEL under operating conditions, and improvements on the thermal model. Although in deriving the thermal diffusivity no need arose for determining the thermoreflectance coefficient, it would be useful to carry out a calibration experiment to determine this parameter.

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