Temperature Analysis of Threshold Current in Infrared Vertical-Cavity Surface-Emitting Lasers

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Abstract—The temperature dependence of threshold current I_{th} in vertical-cavity surface-emitting lasers (VCSELs) can be approximated by the equation $I_{th}(T) = \alpha + \beta(T - T_{min})^2$, where T_{min} is the temperature of lowest I_{th}, α and β are parameters, and temperature is T. We compare the temperature dependence of threshold current in VCSELs with GaAs, InGaAs, and strain compensated InGaAs–GaAsP quantum wells. From our analysis we find the coefficient β is related to the gain properties of the quantum well, and is shown to serve as a benchmark for the VCSEL temperature sensitivity. The incorporation of strain-compensated high-barrier GaAsP layers in the active region of 980-nm VCSELs is demonstrated to reduce the threshold dependence on temperature.

Index Terms—Diode lasers, temperature analysis, threshold current, vertical-cavity surface-emitting lasers (VCSELs).

I. INTRODUCTION

VERTICAL-CAVITY surface-emitting lasers (VCSELs) have emerged as a promising light source for short-haul high-speed optical data communication and optical interconnections between electronic circuits on board-to-board and perhaps chip-to-chip levels. VCSELs are attractive in these applications due to wafer-scale manufacturability, on-wafer testing, ease of packaging, and the ability to fabricate two-dimensional laser arrays. Moreover, VCSELs are advantageous over conventional edge-emitting lasers because of a low divergent circular output beam, low threshold current, single longitudinal mode emission, and inherent high-speed modulation [1]. A number of applications require VCSELs to operate reliably over a broad temperature range. Changes in VCSEL performance with temperature are primarily related to a temperature-induced spectral misalignment of the cavity resonance and laser gain bandwidth [2].

In order to improve performance at elevated temperature or reduce sensitivity to temperature change, it is important to establish a criterion for VCSEL temperature sensitivity with which different devices can be compared. In the case of edge emitting lasers, the characteristic temperatures T_0 and T_1, which are the coefficient of temperature dependence on threshold current and the coefficient of temperature dependence on external differential efficiency, respectively, have long

been employed as benchmarks to compare different material structures [3]–[5]. However, a similar parameter for VCSEL performance is not commonly compared, although the temperature characteristics of VCSELs have been observed and analyzed in many earlier studies [2], [6]–[10]. In this work we analyze the temperature dependence of threshold current in VCSELs with different quantum well active regions. We find an appropriate benchmark parameter for VCSELs that enables comparison between different VCSEL structures. Moreover, using this analysis we show strain-compensated high-barrier GaAsP layers in 980-nm VCSELs with InGaAs quantum wells have reduced temperature sensitivity compared to conventional 980-nm VCSELs without strain compensation.

In Section II, we analyze the temperature dependence of threshold current in VCSELs. We show that it is appropriate to fit the warm side of the threshold current versus temperature curve with a second-order polynomial equation. The warm side of the curve corresponds to the short wavelength side of the gain spectrum, which is in turn governed by the Fermi–Dirac statistics of the carrier occupation probability. A fitting coefficient β is found to be inversely proportional to the effective electron and hole mass in the quantum wells. In Section III, we measure and compare the coefficient β from three different VCSEL structures, where the differences in this parameter are attributed to the differences in the degree of strain, leakage current, and Auger recombination in the quantum wells. We show that the coefficient β can serve as a benchmark for VCSEL temperature sensitivity. Strain-compensated high-barrier quantum wells which have reduced values of the coefficient β will aid the development of lower temperature sensitivity in VCSELs.

II. ANALYSIS

Unlike edge emitting semiconductor lasers, a single longitudinal cavity mode due to the short cavity length of a VCSEL spectrally overlaps the gain bandwidth. Lasing occurs at the frequency of this single cavity resonance. The longitudinal mode of a VCSEL also must spatially overlap the quantum wells in the active region. The spectral alignment between the laser gain and cavity resonance in VCSELs is known to dominate the temperature dependence of the threshold current. The minimum threshold current occurs approximately at the temperature where the cavity resonance is spectrally aligned with the maximum gain [2], [11], [12]. We denote this temperature as T_{min}. Any temperature deviation from T_{min} results in spectral misalignment between the maximum material gain and the cavity resonance. Spatial effects, such as temperature induced changes of the overlap between the optical mode and
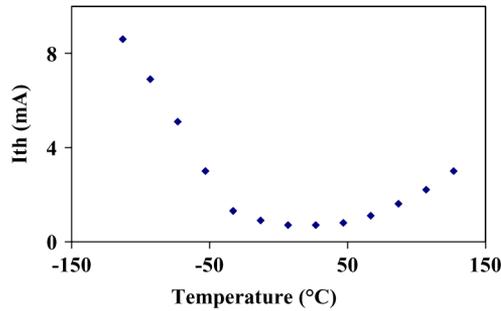
Fig. 1. Measured temperature dependence of threshold current for an 850-nm VCSEL.

Fig. 2. (a) Calculated GaAs quantum well gain spectra at a constant carrier density (5×10^{18} cm^{-3}) for different temperatures. The open (closed) circles indicate the gain-resonance overlap as the gain spectra red-shifts (blue-shifts) due to increasing (decreasing) temperature. (b) Material gain at the cavity resonance versus temperature for a constant current density (5×10^{18} cm^{-3}). (Color version available online at: http://ieeexplore.ieee.org.)

the quantum wells are not accounted for in the following analysis. Since the laser gain is fixed at threshold, greater current is needed to maintain the threshold condition. The laser gain red shifts more with temperature than the cavity resonance. For example, the gain bandwidth in 980-nm VCSELs with In$_{0.18}$Ga$_{0.82}$ As quantum wells and 850-nm VCSELs with GaAs quantum wells spectrally shift at 0.33 nm/°C [2] and 0.32 nm/°C [3], respectively. However, the cavity resonances for both VCSELs shift at an approximate rate of 0.07 nm/°C [2], [6]. The misalignment between the peak gain and cavity resonance with changing temperature causes the threshold current to increase, resulting in an approximate parabolic shaped curve as shown in Fig. 1.

A second-order polynomial is employed to fit to the data in Fig. 1

$$I_{\text{th}}(T) = \alpha + \beta(T - T_{\min})^2. \tag{1}$$

In this equation, $I_{\text{th}}(T)$ is the temperature-dependent threshold current where α, β, and $T_{\min}$ are the parameters. The coefficients α and $T_{\min}$ are related to the specific VCSEL structure. The coefficient α is the minimum threshold current which the VCSEL can achieve, which occurs roughly at the temperature which causes the cavity resonance to overlap the peak gain. The minimum threshold current is related to the laser mirror and absorption loss. As discussed previously, $T_{\min}$ is the temperature at which this minimum threshold current occurs. The coefficient β is related to the threshold current change for a given temperature change, which is affected by the degree of the spectral alignment between the peak gain and cavity resonance as temperature varies. The cavity resonance is determined by the effective optical length of the cavity formed between the two distributed Bragg reflectors (DBRs), and it shifts due to temperature-induced change in index of refraction [2], [6]. The laser gain spectrum depends on the material type and thickness of the quantum wells. Therefore, the coefficient β will be influenced by the quantum well design and overall effective index of the cavity, and it can serve as a relative measure of the temperature sensitivity in VCSELs analogous to T_0 for edge-emitting lasers. A larger β coefficient indicates higher sensitivity of threshold current to temperature change.

Some degree of asymmetry is often observed from threshold current measurements of VCSELs over a broad temperature range, such that the cold side of curve is steeper than the
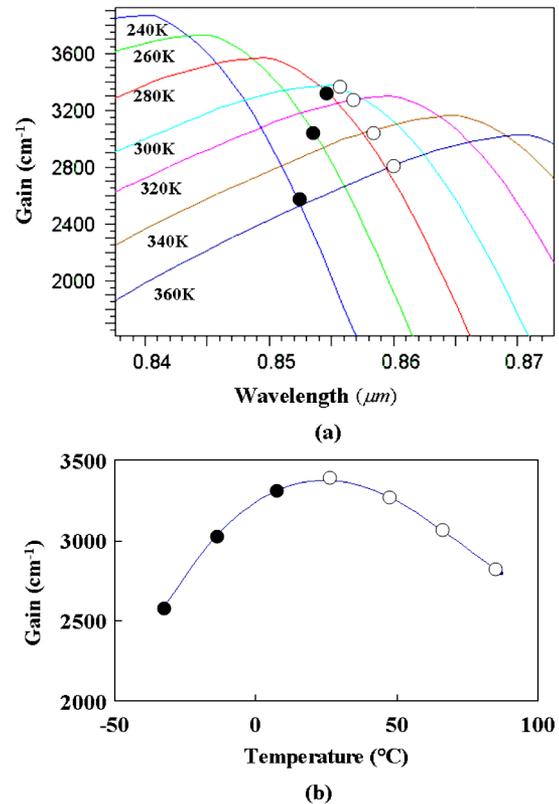
warm side (see Fig. 1) [8]. The shape of the curve arises predominantly from the asymmetry of the gain spectrum. Since the cavity resonance shifts less than the gain peak, it scans the short or long wavelength side of the gain spectrum as the temperature increases or decreases from $T_{\min}$, respectively. As shown in Fig. 2(a), due to the asymmetry of the gain spectrum, the material gain at resonance drops from its maximum value at different rates as the temperature changes. This is explicitly plotted in Fig. 2(b). Because of this asymmetry and due to the typical laser operating conditions, it is convenient to fit only the warm side of the threshold current versus temperature curve and its trend is thus dictated by the short wavelength side of the gain spectrum.

A theoretical gain spectrum for a quantum well structure can be calculated with the expression [13]

$$g(\hbar\omega) = C_0 |M_T|^2 \rho_r(\hbar\omega)(f_c - f_v) \tag{2}$$

where C_0 is the gain constant for a specific quantum well, M_T is the momentum matrix element, $\rho_r(\hbar\omega)$ is a Heaviside function that describes the joint density of states, and f_c and f_v are electron occupation probabilities for the conduction and valence bands, respectively. Other factors such as lineshape broadening and many body effects further modify the gain spectrum [8], [14]. As discussed earlier, the warm side of the temperature dependence of threshold current to be fit is related to the short

wavelength side of the gain spectrum, which is primarily governed by the carrier inversion, $f_c - f_v$. The lineshape broadening and many body effects on the short wavelength of the gain spectrum are less significant. Therefore, the coefficient β which describes the curvature of the warm side of the temperature dependence of threshold current will be proportional to (3), shown at the bottom of the page, where E_g is the bandgap energy, E_{en} and E_{hm} are the nth conduction and mth valence subband energy levels in the quantum wells, F_c and F_v are the quasi-Fermi levels for electrons and holes, K_B is the Boltzmann constant, so $K_B T$ accounts for the thermal energy at temperature T, m_r is the reduced mass, and m_e and m_h are the effective mass for electrons and holes in quantum wells.

From (3) we see that smaller effective electron or hole mass will result in a larger coefficient β. Compressive or tensile strain in quantum wells can reduce the effective electron and hole mass [15]. For example, InGaAs quantum wells have slightly smaller electron and hole mass than GaAs quantum wells. Thus, for 980-nm VCSELs with InGaAs–GaAs compressive strained quantum wells, we expect the β coefficient to be greater than that of 850-nm VCSELs with unstrained GaAs–AlGaAs quantum wells.

Simulations were performed to justify this analysis approach. The injection current and carrier density are related by

$$I = q(\text{Area})d(An + Bn^2 + Cn^3) + I_L \qquad (4)$$

where q is the unit charge, "Area" is the cross-sectional area of the laser cavity, d is the active region thickness, n is the carrier density, I_L is the leakage current, An is due to Schotky–Read–Hall (SRH) nonradiative recombination, Bn^2 is due to spontaneous radiative recombination, and Cn^3 accounts for Auger nonradiative recombination [3]. The VCSEL threshold current is proportional to the threshold carrier density and it should, therefore, follow a similar temperature dependence. In our simulations, laser gain versus carrier density in the GaAs and InGaAs quantum wells described in the next section were calculated at different temperatures. The gain curves are generated using a free carrier gain model which incorporates an 8×8 K·P band structure computation to calculate the density of states and solves the Poisson and continuity equations to determine the quasi-Fermi levels.[1] Assuming a particular threshold gain, γ_{th}, for lasing to occur (determined by the total laser loss), the cavity resonance and laser gain versus carrier
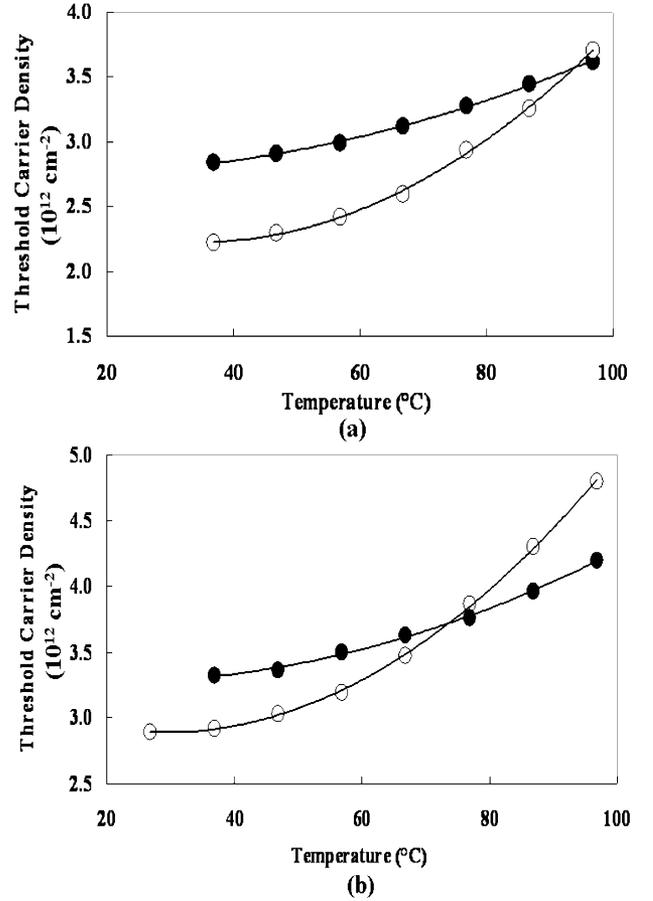
[1]LaserMOD Software, RSoft Design Group

Fig. 3. Plot of the temperature dependence of the sheet carrier density for 80-nm GaAs–AlGaAs quantum wells of 850-nm VCSELs (closed circles) and 80-nm InGaAs–GaAs quantum wells of 980-nm VCSELs (open circles) for (a) $\gamma_{\text{th}} = 1500 \text{ cm}^{-1}$ and (b) $\gamma_{\text{th}} = 2000 \text{ cm}^{-1}$.

density were calculated for a given operating temperature. The spectral intersection of these two curves indicates the threshold carrier density. The same calculation is then repeated at different temperatures, resulting in the temperature dependence of threshold carrier density for a particular threshold material gain, γ_{th}. The threshold carrier density for GaAs and InGaAs quantum wells for two values of γ_{th} are shown in Fig. 3. The temperature dependence of threshold carrier density is fit with a second-order polynomial. From Fig. 3 it is apparent that the GaAs–AlGaAs quantum wells tend to have less dependence on temperature (less curvature) than the InGaAs–GaAs quantum wells.

$$
\begin{aligned}
\frac{\partial(f_c - f_v)}{\partial(\eta\omega)} &= \frac{m_r/m_e}{K_B T} \cdot \left\{ \frac{1}{1 + \exp\{[E_g + E_{en} + (m_r/m_e)\eta\omega - F_c]/K_B T\}} \right\}^{-2} \\
&\quad \times \exp\{[E_g + E_{en} + (m_r/m_e)\eta\omega - F_c]/K_B T\} \\
&\quad - \frac{m_r/m_h}{K_B T} \cdot \left\{ \frac{1}{1 + \exp\{[E_{hm} - (m_r/m_h)\eta\omega - F_v]/K_B T\}} \right\}^{-2} \\
&\quad \times \exp\{[E_{hm} - (m_r/m_h)\eta\omega - F_v]/K_B T\}
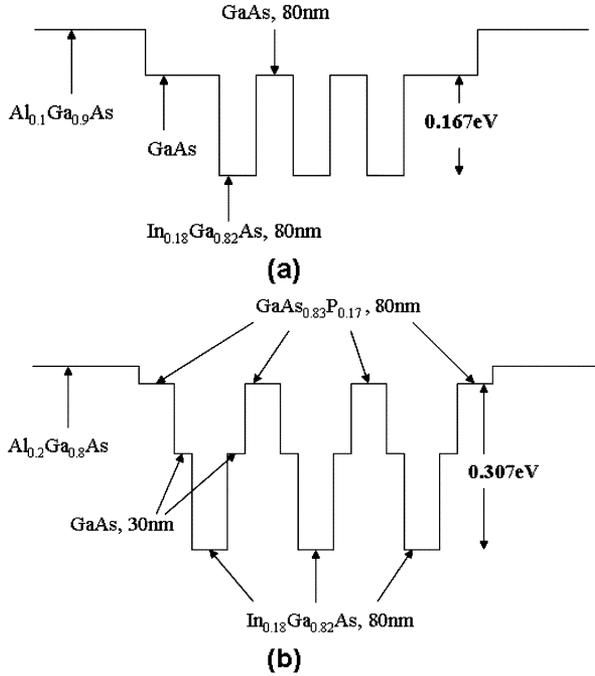\end{aligned} \qquad (3)
$$

Fig. 4. Schematic diagram of the conduction band edge for the quantum well region and cladding layers in the 980-nm (a) Laser I and (b) Laser II. Energy band offset is calculated at 300 K and $\Delta E_c = 0.65 \, \Delta E_g$ is assumed [13], [16].

III. EXPERIMENT

A. Device Structure

VCSELs with three different quantum well structures are fabricated and characterized. Laser I and II are designed for 980-nm laser operation. The active region of Laser I shown in Fig. 4(a) contains 3 $In_{0.18}Ga_{0.82}As$–GaAs quantum wells. The lower and upper cladding layers are n-type $Al_{0.1}Ga_{0.9}As$ and p-type $Al_{0.1}Ga_{0.9}As$, respectively. The quantum well depth in the conduction band is 0.167 eV at 300 K. For Laser II, tensile-strained $GaAs_{0.83}P_{0.17}$ layers are inserted between the InGaAs quantum wells as shown in Fig. 4(b). The lower and upper cladding layers are n-type $Al_{0.2}Ga_{0.8}As$ and p-type $Al_{0.2}Ga_{0.8}As$, respectively. The quantum well depth in the conduction band is 0.307 eV at 300 K. Note that the deeper quantum wells as compared to Laser I result from the $GaAs_{0.83}P_{0.17}$ layers. Both Laser I and II contain similar top and bottom quarter-wavelength DBR mirrors with 23 and 36 periods, respectively. The third laser structure, Laser III, is designed to operate at 850-nm and contains 5 GaAs–$Al_{0.2}Ga_{0.8}As$ quantum wells. The lower and upper cladding layers of Laser III are n-type $Al_{0.2}Ga_{0.8}As$ and p-type $Al_{0.2}Ga_{0.8}As$, respectively, which creates a 0.167 eV well depth. The top and bottom DBR mirrors have 21 and 36 periods, respectively.

Lasing apertures for all lasers are defined using selective oxidation [1], and all characterization and comparisons in this work are for 5×5-μm oxide aperture devices. The lasers are placed on a temperature-controlled stage, and the light output versus current (L–I) characteristics are measured by on-wafer probing under continuous wave (CW) operation using a semiconductor parameter analyzer and a calibrated silicon photodetector. Threshold current versus temperature for each sample is obtained
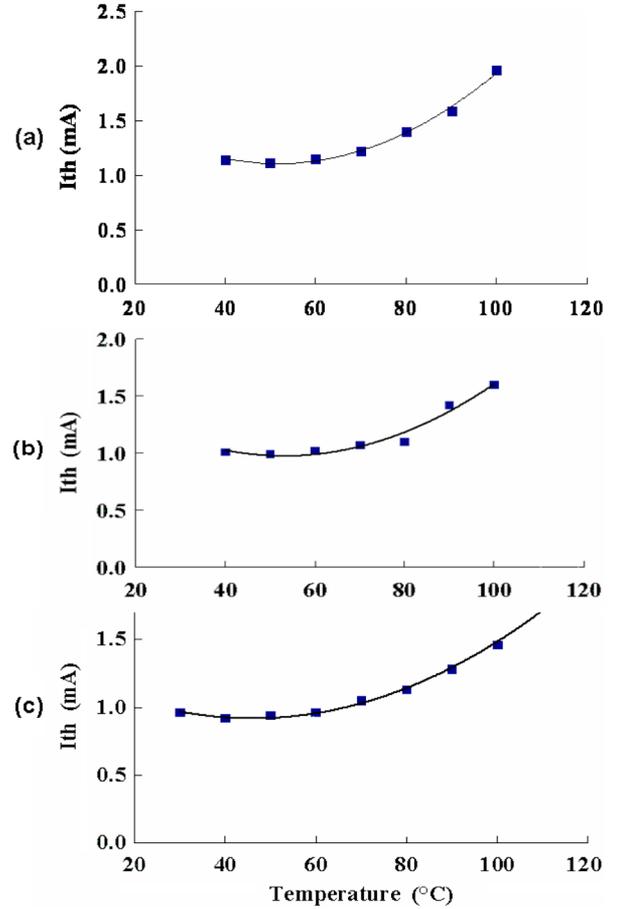

Fig. 5. Measured VCSEL temperature dependence of threshold current for (a) 980-nm Laser I–Sample 1, (b) 980-nm Laser II—Sample 1, and (c) 850-nm Laser III.

TABLE I
FIT PARAMETERS FOUND FROM THE TEMPERATURE DEPENDENCE OF THRESHOLD CURRENT

	α, (mA)	β, ($\mu A/°C^2$)	T_{min}, (°C)
980nm, Laser I, Sample 1	1.103	0.354	51.55
980nm, Laser I, Sample 2	1.055	0.348	54.31
980nm strain compensated, Laser II, Sample 1	1.248	0.271	47.42
980nm strain compensated, Laser II, Sample 2	0.976	0.287	53.13
850nm, Laser III	0.918	0.194	46.13

at temperatures ranging from 30 °C to 110 °C. Examples of the measured threshold current are shown in the plots of Fig. 5.

B. Results

Using data sets such as shown in Fig. 5, the coefficients α, β, and T_{min} were calculated using (1) for several samples and are listed in Table I. As shown in Table I, the coefficient β varies slightly between VCSELs with a particular quantum well structure; however a greater variation is noticed between different laser structures. Note that the minimum threshold current (α)

and the temperature where this occurs $(T_{\min})$ does vary among samples from the same wafer, as expected due to wafer non-uniformity [17]. Two other observations can be made: first, the 980-nm VCSELs (Laser I and Laser II) generally have larger β coefficients than 850-nm VCSELs (Laser III); secondly, the 980-nm VCSELs with strained quantum wells (Laser I) generally have larger β coefficients than those with a strained compensated quantum well design (Laser II).

The first observation is consistent with 980-nm VCSELs with compressive strained quantum wells having reduced effective hole mass and thus having a larger coefficient β than 850-nm VCSELs with unstrained quantum wells. Note that 850-nm VCSELs with GaAs–$Al_{0.2}Ga_{0.8}As$ quantum wells have the same well depth in the conduction band at 300 K as 980-nm VCSELs with $In_{0.18}Ga_{0.82}As$–GaAs quantum wells. Thus, both VCSEL structures should have a similar degree of carrier confinement in the quantum wells. Another explanation for 980-nm VCSELs generally having a larger coefficient β than 850-nm VCSELs is that InGaAs quantum wells exhibit greater Auger recombination than GaAs quantum wells. The Auger recombination coefficients of GaAs quantum well for 850 nm and InGaAs quantum well for 980-nm lasing operation are approximately 3.5×10^{-30} cm^6/s and 10^{-29} cm^6/s, respectively [2], [18], [19]. Even though Auger recombination at 850 and 980 nm is not as significant as it is at longer wavelength [15], greater Auger recombination in 980-nm InGaAs VCSELs will contribute to increased temperature sensitivity compared to 850-nm GaAs VCSELs.

In order to improve VCSEL performance over a broad temperature range, it is desirable to reduce the temperature sensitivity. The benefit of introducing tensile-strained or strain-compensated GaAsP layer to achieve long-wavelength and high-temperature laser operation is evident from the performance of Laser II. Improvement in crystal quality and carrier confinement for quantum wells containing GaAsP reduces the leakage current and thus lowers the temperature sensitivity of threshold current, resulting in a larger characteristic temperature T_0 for edge-emitting quantum well lasers [20]–[23]. From Table I, it is evident that 980-nm VCSELs with strain-compensated high-barrier $GaAs_{0.83}P_{0.17}$ layers also exhibit about 20% lower temperature sensitivity as compared to strained quantum wells. The smaller coefficient β for the VCSELs with the strain-compensated GaAsP layers is attributed to the reduction of compressive strain and improved carrier confinement in the quantum wells.

IV. Conclusion

In summary, we have shown the temperature dependence of threshold current in VCSELs can be approximated by $I\mathrm{th}(T) = \alpha + \beta(T - T_{\min})^2$. This expression provides a useful tool to analyze VCSEL temperature characteristics. The coefficient β serves as an important benchmark for VCSEL temperature sensitivity (smaller β is better), and can be a figure of merit for how threshold current changes with temperature. The coefficient β is dependent on quantum-well active region material and design. We have shown experimentally that 980-nm VCSELs exhibit a larger β coefficient than 980-nm VCSELs with high-barrier strain-compensated layers, which in turn are larger than the β coefficient found for 850-nm VCSELs. Smaller temperature sensitivity will enable VCSELs to operate more reliably under a

high temperature environment, and will also extend VCSEL operation to higher current, allowing for higher power operation.

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