Vixar Application Note

VCSEL Reliability Methodology

Contents

1 Executive Summary

There are many functions for vertical cavity surface emitting lasers (VCSELs) that span over the consumer, industrial, and automotive markets. Such applications include consumer gesture recognition sensors, security camera illumination, industrial metrology, medical sensors, light therapy, laser printing, and high-speed communications. Each application will have a desired VCSEL lifetime requirement, and the reliable operation of VCSELs over the lifetime of the application is an extremely important requirement. Reliability testing is required to ensure that high-quality products are designed properly.

Vixar has performed and continues to conduct reliability testing on our VCSEL devices to ensure the reliability performance that our customers demand. This paper presents the reliability methodology used at VIXAR to determine the lifetime of Vixar's VCSEL products and how the device 'use-conditions' can impact the device lifetime. However, due to the variety of applications, VCSEL designs, and operating conditions, it is not the goal of this application note to give detailed reliability data. Based upon customer-specific requirements, Vixar will provide reliability data to customers relevant to their preferred product and operating conditions.

2 Reliability Requirements of VCSEL Applications

VCSEL lifetime is primarily a function of the interaction between the factors listed below [2].

- Junction temperature
    - Ambient temperature
    - Nonradiative power dissipation
- Current density
- Humidity
- Duty Cycle
- Pulse width

Apart from the VCSEL design, including aperture diameter and epi structure, these are use condition properties. The lifetime of the VCSEL is very dependent on these factors, so each customer's unique application can cause meaningful changes in the VCSEL's lifetime. The driving conditions will impact the Light-Current-Voltage (LIV) performance of the VCSEL over time.

Distinct applications will have different reliability requirements. Applications that are used 24/7 and have serious financial or societal ramifications upon failure require very high reliability for all the critical components. For example, downtime for a central office communication network switch with a VCSEL as a fiber optic transmission light source may be very expensive. In contrast, an array of hundreds of VCSELs providing optical power for low light therapy will have no significant impact on the application when a small number of failures occur.

3 Reliability Modeling

VCSEL device failures due to “wear-out” have been found to best fit a lognormal or Weibull distribution **Error! Reference source not found.**. A fit to the cumulative failure rate of devices under accelerated aging or stress conditions allows for the calculation of time-to-failure (TTF) data. To calculate TTF under normal operating conditions from the TTF determined at the accelerated aging conditions, a model is needed on how the TTF varies with temperature and drive current. This is usually expressed as an acceleration factor *(AF)*, where

$$AF = \left(\frac{I_1}{I_2}\right)^n \; exp\left(\frac{E_A}{k_B}\left(\frac{1}{T_{j2}} - \frac{1}{T_{j1}}\right)\right)$$

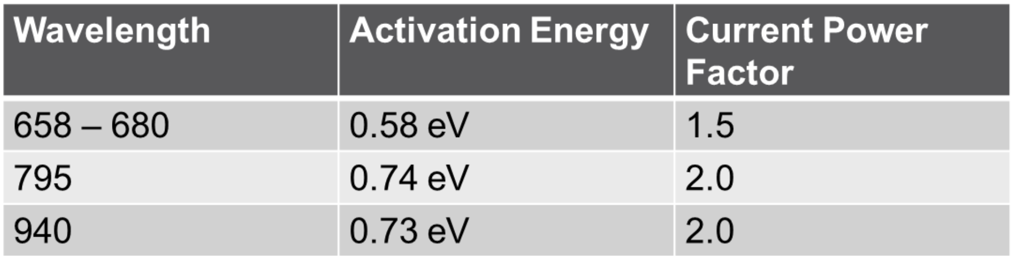
E_A is the activation energy, n is the power law dependence of current density, and k_B is Boltzman’s constant. $I_{1,2}$ is the drive current at junction temperatures $T_{j1,2}$. The junction temperature T_{ji} of the VCSEL die is given by

$$T_{ji} = T_{ambient} + R_{th} * (I_i * V_i - P_i)$$

where $(I_i * V_i - P_i)$ is the input power converted to heat (input electrical power minus the emitted optical power), and R_{th} is the thermal resistance of the VCSEL. The R_{th} for single apertures ranges from 1.4 K/mW for multimode devices to 2.7 K/mW for single mode devices. This junction temperature calculation assumes continuous-wave (CW) operation of the VCSEL. When driving VCSELs under pulsed operation with short pulse widths (<100 µs), the junction temperature would be reduced by a correction factor that depends on the duty cycle (see section 4.2.1). Short pulse periods do not allow the heat to build up in the aperture region and allow time for the die to cool down between current pulses.

To apply the *AF* on evaluating device TTF, E_A and n both need to be determined experimentally through extensive reliability testing. The data from other VCSEL manufacturers and from VIXAR’s testing all indicate that typically E_A = 0.7eV and n = 2 0. We have confirmed the values shown in table 1 below by testing various epi structures at different current and temperature values.

Table 1. Activation energy and power factor values determined for Vixar devices.



Wavelength	Activation Energy	Current Power Factor
658 – 680	0.58 eV	1.5
795	0.74 eV	2.0
940	0.73 eV	2.0

High temperature operating life (HTOL) testing is performed at accelerated conditions. The temperatures used for these tests are typically 85 °C, 105 °C, and 125 °C. Because the LIV performance, junction heating, and other characteristics differ for each VCSEL design, the test current ranges are customized for each product. Example temperature and currents for three different products are shown below in Table 2. The burn-in temperatures and currents for each product are selected to yield results that produce practical output power while still attempting to produce sufficient failures (>20% reduction in output) for statistically significant curve fitting to the reliability model.

Table 2: Dry Test Conditions for 3 different VCSEL Families for single mode (SM) and multi-mode (MM) VCSEL die.

SM	**85° C**	**105° C**	**125° C**
1 mA			X
2 mA	X	X	X
3 mA	X	X	

MM	**85° C**	**105° C**	**125° C**
9 mA			X
11 mA	X	X	X
13 mA	X	X	

For each VCSEL product, 16-32 devices are tested at each condition for a total of 192 devices for each VCSEL family. They are removed periodically from the burn-in ovens, allowed to cool down for over 1 hour, and measured for LIV performance at room temperature. Testing continues until enough failures have occurred at various accelerated conditions to build a lifetime model. For example, Figure 1 shows the test results for a device stressed at 2.5 A at 115C. Since multiple failures occur among the tested devices, this information can be used to create a Weibull distribution for this product.

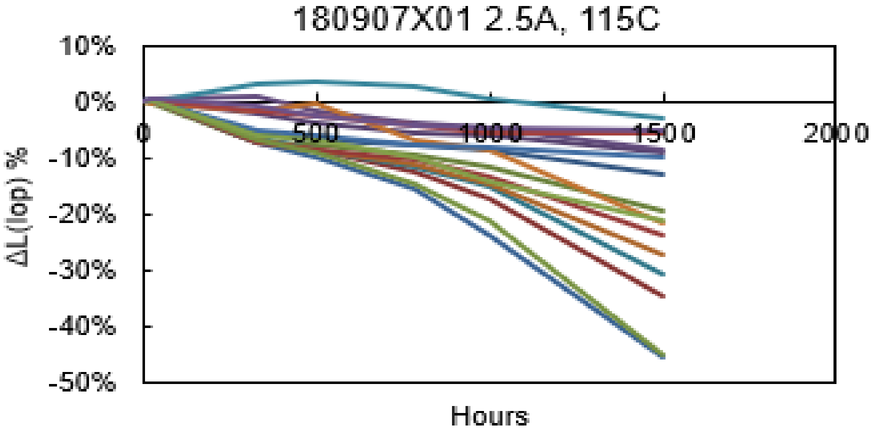


Figure 1. Results of high temperature operating life testing.

Once enough failures have occurred among all the different test conditions, the data is fed into a statistical program, such as Reliasofts's Weibull++ or Minitab, for analysis. The data must first be evaluated to ensure it fits the lognormal distribution that is expected for device wear out. Figure 2 shows an example of a Weibull distribution. If the data does fit a lognormal or Weibull distribution, acceleration factors can be used to calculate lifetime statistics. The important parameters in the Weibull distribution are the slope (Beta = 5.6) and the characteristic life (Eta = 1420 hours). These parameters, along with the *AF*, can be used to predict the life under any customer-specific use conditions.

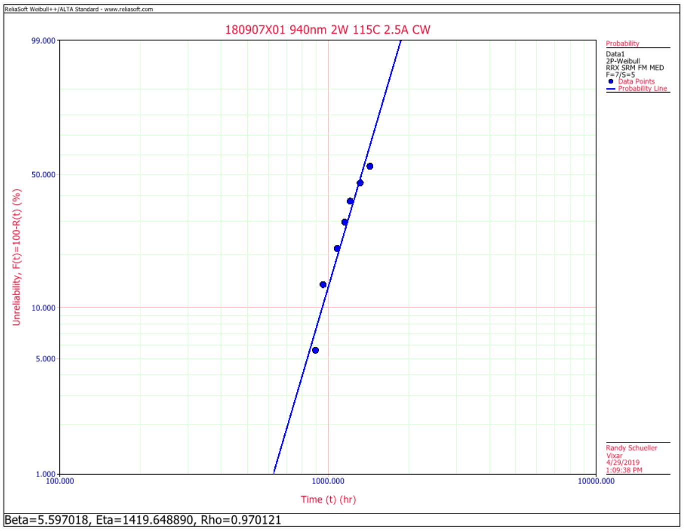


Figure 2. A Weibull distribution representing device failures.

The life of the VCSELs can be estimated for numerous user applications based off the Weibull parameters. A "meta-analysis" can be conducted once the acceleration factors are determined for each operating environment, including high ambient temperatures. This translates the acceleration factors into the individual failure times in reference to a common use condition and provides an estimate of the distribution of failures in time.

These failure distributions allow us to estimate VCSEL TTF performance over different operating conditions for the same device. TTF values are typically determined over a range of ambient temperatures that cover what might be observed in the end-use application, as shown in Figure 3. These lifetime values can also be plotted or a range of different driving currents and pulse conditions if the application requires operation at various emission levels.

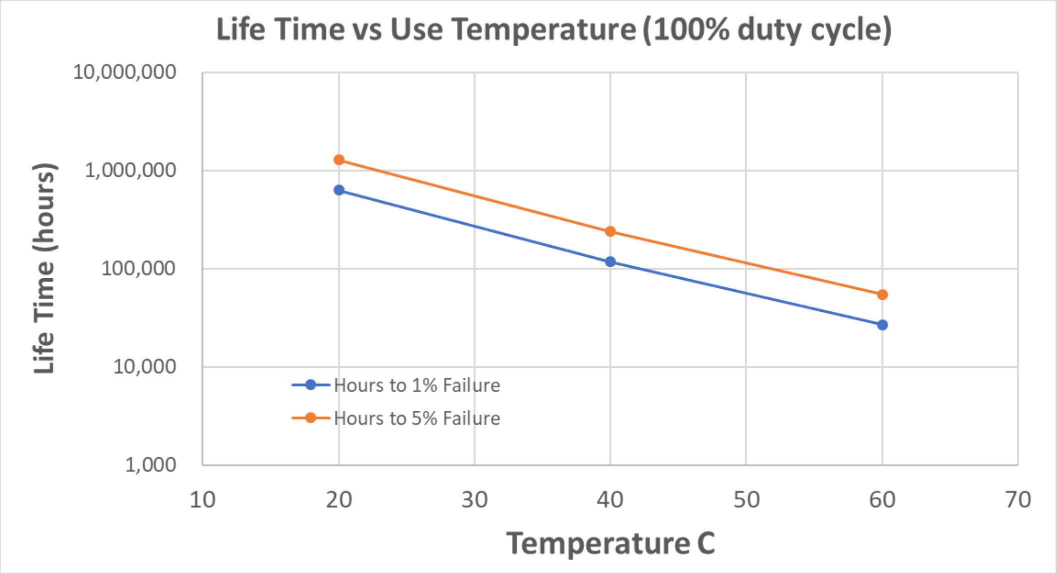


Figure 3. An example showing time to 1% failure and 5% failure at various temperatures.

3.1 Dry Pulsed Test

When power is initially applied to a VCSEL, no optical power is observed until the forward current surpasses the threshold current (I_{th}). Beyond threshold, the output power initially increases linearly with increasing forward current. However, the nonradiative power dissipation inside the die starts to reduce the power conversion efficiency, and the slope efficiency (W/A) starts to decrease until it flattens out and reaches a maximum output power (P_{max}) at a current defined as I_{max}. As the current is increased beyond I_{max}, the slope efficiency becomes negative, and optical power decreases with increasing current. This is rollover phenomena at I_{max} is known as "thermal rollover."

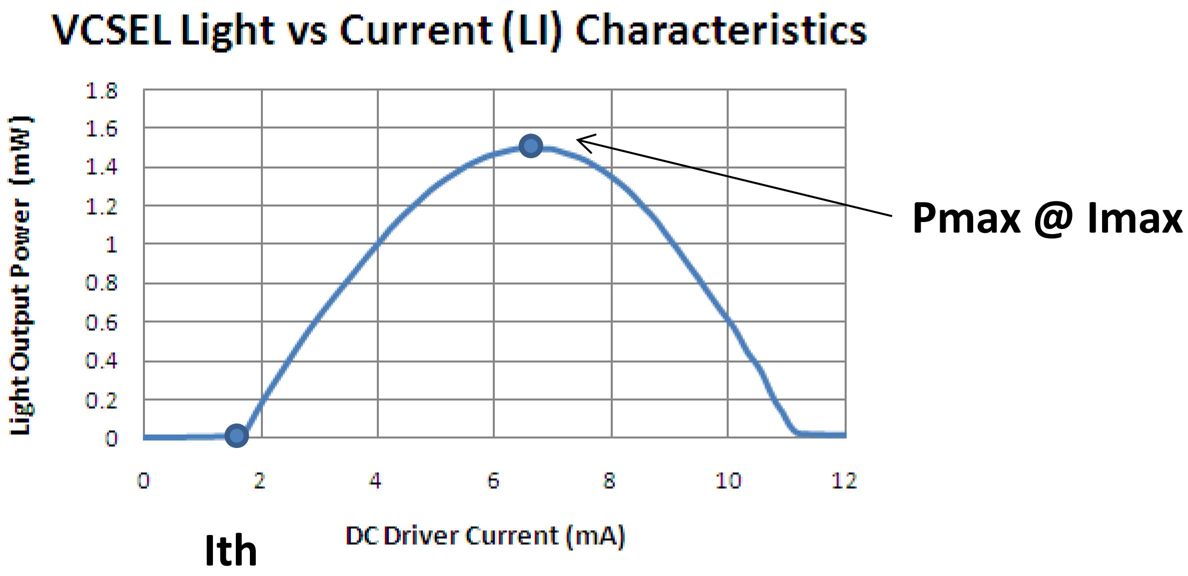


Figure 4: Thermal rollover observed in a plot of VCSEL output vs drive current

The thermal heating inside the VCSEL die can be reduced by the application of short current pulses at reduced duty cycle. The reduced junction heating results improve slope efficiency over current, increasing the value of I_{max} where thermal rollover occurs. Thus, pulsing can achieve higher instantaneous output power when compared to CW operation at the same temperature. Figure 5 shows an example of thermal rollover during CW and pulsed conditions for a single aperture VCSEL. For a detailed explanation, see VIXAR's Application Note "Operation of VCSELs Under Pulsed Conditions -- Increasing VCSEL Output Power" [4].

Besides providing more power at higher currents and temperatures, pulsed operation also provides a longer VCSEL lifetime in many situations. As the current pulse width driving the VCSEL becomes shorter, the junction heating effect becomes smaller. The lifetime of the product is improved since the VCSEL's junction temperature is reduced.

The effective lifetime will further increase since the device is operational only for a percentage of each cycle. For instance, a 12.5% duty cycle should increase the lifetime by a factor of eight. However, if more current is required to obtain the desired optical power, then the lifetime will be reduced due to this higher current. The gains in lifetime from reduced junction temperature and duty cycle must be weighed against the lifetime loss due to the increased drive current.

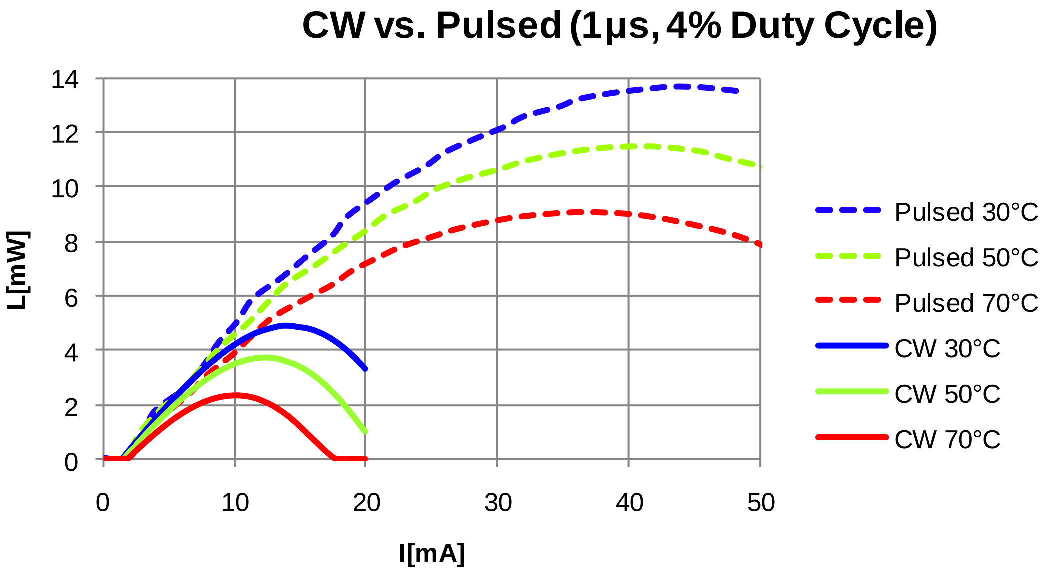


Figure 5: Power output for a single aperture VCSEL under CW and pulsed conditions

The junction temperature vs. rollover emission for a 4W device is shown in Figure 6. Emission ceases at the Y-intercept junction temperature, because VCSELs are not able to produce optical power above a certain junction temperature. For CW conditions, this temperature is 150°C. However, when driven at 10% duty cycle with a 100 µs pulse, calculations would show that VCSEL emission ceases at 200°C. Due to this discrepancy, a correction factor needs to be included into junction temperature calculations when VCSELs are driven under a 100% duty cycle. This correction factor is essential when making life estimates for applications where a low duty cycle is used. For example, the actual junction temperature when running at 10% duty cycle with a 100 µs pulse is determined by multiplying the nonradiative power dissipation by 0.75.

$$T_{ji}(@10\%\ DC) = T_{ambient} + R_{th} * (I_i * V_i - P_i) * 0.75$$

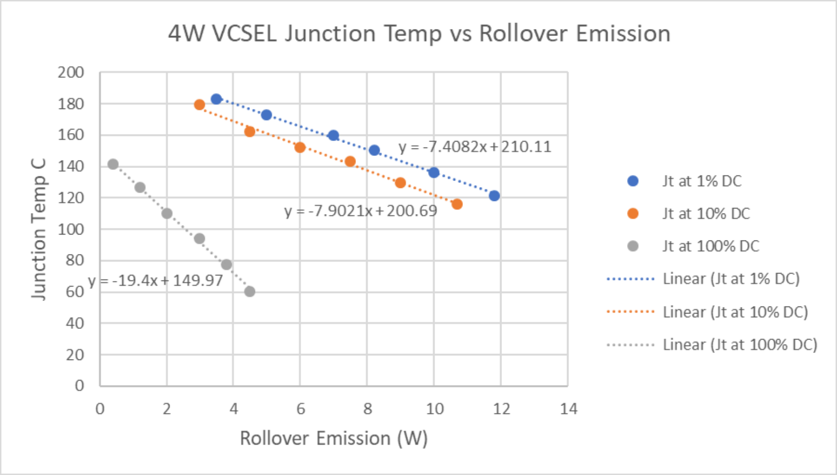
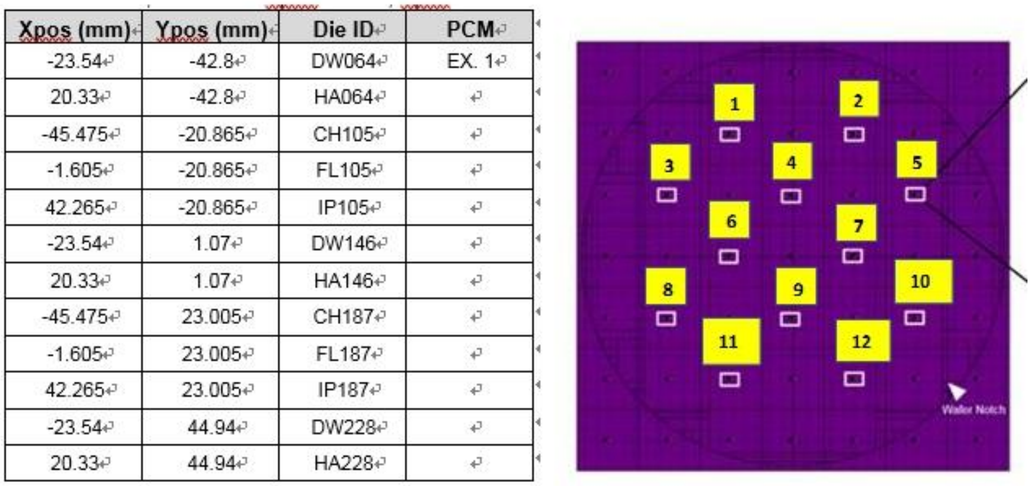


Figure 6. Junction temp vs rollover emission for a 4W VCSEL power array

3.2 *Wafer Qualification Testing*

Each lot of wafers produced by the fab are subject to wafer qualification and on-going reliability testing. Vixar selects 12 die from across the wafer, as shown in Figure 7, and stress tests them for 168 hours under CW current conditions at an elevated temperature. The stress conditions are selected to ensure that the devices will meet the customer requirements. For example, a 2W device might be run at 2.5A CW at 105°C. If none of the VCSELs exhibit a power loss of >20%, then the wafer lot will meet design requirements.



Xpos (mm)	Ypos (mm)	Die ID	PCM
-23.54	-42.8	DW064	EX. 1
20.33	-42.8	HA064	
-45.475	-20.865	CH105	
-1.605	-20.865	FL105	
42.265	-20.865	IP105	
-23.54	1.07	DW146	
20.33	1.07	HA146	
-45.475	23.005	CH187	
-1.605	23.005	FL187	
42.265	23.005	IP187	
-23.54	44.94	DW228	
20.33	44.94	HA228	

Figure 7. Die locations across the wafer used for wafer qualification testing

3.3 Humidity Test

Vixar's products are tested for high humidity high temperature at 85°C and 85% humidity. Humidity testing is performed with devices that are directly exposed to the environment. The current used for this non-hermetic testing is just above threshold, so heating doesn't repel the ambient moisture. High current heats the surrounding air and reduces the relative humidity in the environment surrounding the VCSEL. In the case of the humidity testing, VCSELs only age when they are under operation [6].

Typically, 32 devices are tested for humidity resistance. Test devices are periodically removed from the humidity chamber, and LIV measurements are taken at room temperature. Device testing continues for a minimum of 1000 hours. Vixar does humidity testing as a qualification type of test, which is typical throughout the VCSEL industry. VCSELs are designed to last over 1000 hours without any failures. Most humidity failures are abrupt and catastrophic, which contrasts with the gradual wear-out mechanisms observed during dry accelerated aging. Devices that fail humidity testing are sent through failure analysis to determine the root cause of the failure.

4 Conclusions

Reliability testing is continuously ongoing at Vixar for all of its products. Vixar has collected data on thousands of devices for each product, consisting of tens of thousands of hours of accelerated temperatures and currents. This translates into millions of hours under standard use conditions. This data is used to create estimates of lifetime for each customer's specific use conditions.

Use of the appropriate VCSEL family will result in optimal reliability while still meeting the other requirements of the application. These factors include maximum ambient temperature, minimum output power, optical beam shape, and wavelength spectrum. Pulsed mode operation offers a possible solution when higher reliability, higher output power, or higher use temperatures are needed for any VCSEL family.

5 References

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