Vixar Application Note

VCSEL Reliability Methodology

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1 Executive Summary

There are many applications of visible (red) and near IR vertical cavity surface emitting lasers (VCSELs) including consumer gesture recognition sensors, illumination for security cameras, industrial metrology, medical scanning, medical sensors, neurostimulation, low light therapy, laser printers, and high speed communications over glass and plastic optical fiber (POF).

The reliable operation of VCSELs over the lifetime of the application is an extremely important requirement. At Vixar, we have performed and continue to perform reliability testing on our VCSEL devices to ensure the reliability performance that our customers demand. In this paper we present the reliability methodology used at VIXAR to determine the lifetime of our VCSEL products and how the device 'use conditions' can impact the device lifetime. However, due to the variety of applications, VCSEL designs and products, 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 Factors in VCSEL Reliability

VCSEL lifetime is primarily a function of the interaction of the factors listed below [3].

- Junction temperature
  - Ambient temperature
  - Heating due to nonradiative power dissipation
    - Drive Current
    - Aperture diameter
- Current density
- Humidity
- Duty Cycle
- Pulse width (if pulsed)

All but one (aperture diameter) of these is a use condition. The lifetime of the VCSEL is very dependent on use conditions, so each customer's unique conditions can cause meaningful changes in the VCSEL lifetime.

3 Reliability Requirements of VCSEL Applications

Different applications have different reliability requirements. For example, applications that are used 24/7 and have serious financial or societal ramifications upon failure require very high reliability for all the critical components. An example is a central office communication network switch, in which a VCSEL might be a fiber optic transmission light source and downtime may be very expensive. Another example might be neurostimulation for mitigation of Parkinson disease symptoms, in which failure may effectively immobilize the user. An example at the other end of the spectrum is an application in which an array or panel of hundreds of VCSELs provides light for low light therapy, and a small number of failures will likely have no significant impact on the application.

4 Reliability Modeling

VCSEL device failures that are due to “wear-out” have been found ([1], [3], [4]) to best fit a lognormal or Weibull distribution. A fit to the cumulative failure rate of devices put under accelerated aging or stress conditions (some of which are not practical for normal operation) allows for calculation of time-to-failure data (TTF). To calculate TTF under normal operating conditions from the TTF determined at the accelerated aging conditions, we need to have a model of how the TTF varies with temperature and drive current. This is usually expressed as an acceleration factor *(A.F)* which takes the form:

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

E_A is the activation energy, n is the power law dependence of current density, both of which are to be determined experimentally, 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} is given by, for example

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

where (I_i * V_i – P_i) is the input power converted to heat (input power minus the optical power emitted) and R_{th} is the thermal resistance of the VCSEL, which ranges from 2.7°K/mW for SM devices to 1.4°K/mW for MM devices.

The data from other 670-850nm VCSEL manufacturers ([2], [3], [4]) and from VIXAR’s testing all indicate that E_A = 0.7eV and n = 2.

These values for E_A and n show that the lifetime of the device is very dependent on the current and temperature experienced during operation. To demonstrate the relationship of temperature and current to the lifetime of the device let’s look at an example case for a particular VCSEL product.

Use Condition 1: Temperature = 20° C and Current = 2.5 mA
Use Condition 2: Temperature = 25° C and Current = 3.2 mA

Using the equations above and the ‘use conditions’ of this device, the acceleration factor of condition 2 to condition 1 is 3.4. The temperature increase contributes an acceleration factor of 1.6, whereas, the current increase contributes 2.1. These accelerating factors are multiplied together to get the 3.4 overall increase in the acceleration of the device wear out. Suppose the calculated time to 1% failure, TT1%F, was 30,000 hours (3.4 years) under condition 1. This means that it will be 30,000 / 3.4 =~8823 hours (1.0 years) under condition 2. The change in temperature and current from condition 1 to condition 2 may seem small, but in this case it had a rather large impact on device life. The effect of temperature and current to the life of the device can vary from one device type to another. Since the drive current of a smaller aperture device is small to begin with, and the current dependence is squared, and increase of 1mA in drive current has a much bigger impact that for a larger device. In addition the higher thermal impedance of smaller devices results in a faster increase of junction temperature with increased.

Test Conditions and Procedures

Three types of reliability tests are ongoing at VIXAR: dry (no humidity); high humidity; dry pulsed. The test conditions, test procedure, and data analysis methods are presented for each of these.

Devices for all tests are packaged, usually in TO-46 headers. Devices tested in dry conditions have a lid with a window that is sealed to the TO-46 header. Devices tested in high humidity have the window removed so that the die is fully exposed to the environment in the chamber.

A combination of ambient temperature, drive current, and (in some cases) humidity are used to stress the devices and accelerate the aging process. The temperature of the devices that is relevant in the aging process is the junction temperature, which is a combination of the ambient temperature and the internal heating due to the thermal resistance of the materials.

During testing the devices are continuously operated at the indicated temperature and current (and humidity, where appropriate) except when they are removed from these conditions to take LIV (Light output (L) and Voltage (V) versus Current (I)) measurements at room temperature.

In the case of the humidity testing, it is worth noting that the TTF of some electronic devices improves when tested with current applied as compared with no current. This is not the case with VCSELs, which demonstrate a lower TTF in humidity testing with current applied than when tested without current applied [6].

If failures are detected in most devices under test in a particular set of conditions, testing for that set of conditions is halted and the data is fit to an empirical model (see "Reliability Modeling") to calculate the acceleration factor. Failure is typically defined as a 3dB reduction in output power at the specified current, but can change based upon the application.

4.1 Dry Test

4.1.1 Dry Test Conditions

The temperatures used for these tests are typically 85 °C, 105 °C, and 125 °C. Because the LIV, junction heating, and other characteristics differ from one device type to the next, the test current ranges are customized for each product. Example temperature and currents for three different products are shown in Table 1 below. The burn-in temperatures and currents for each product are selected to yield results in the ranges of current and temperature that produce practical output power, and yet still attempt to have sufficient failures (in the high temperature and high current case) for statistically significant curve fitting to the reliability model. SM= Single Mode, MM=Multi-Mode, and CG= Communications Grade. CG is also a multi-mode device, but with an aperture size optimized for high speed operation.

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	

CG	85° C	105° C	125° C
5 mA			X
7 mA	X	X	X
8 mA	X	X	

Table 1: Dry Test Conditions for 3 different VCSEL Families

4.1.2 Dry Test Procedure

For each VCSEL product, 32 devices are typically tested at each condition for a total of 192 devices for each VCSEL family. They are removed periodically from the burn-in ovens and LIV measurements are taken at room temperature. Testing continues until enough failures have occurred at various accelerated conditions to calculate a lifetime.

4.1.3 Dry Test Analysis

Once sufficient failures at various currents and temperatures have occurred, the data is fed into a statistical program such as Reliasofts's Weibull++ or Minitab for analysis. First we make sure that the data fits the lognormal distribution that we expect for wear out. If the data does fit a lognormal or Weibull distribution, we then use the acceleration factors for temperature E_A and current (n) that the software calculates to calculate lifetime statistics.

Once the acceleration factors are found, we then perform a "meta-analysis", i.e., we use the calculated acceleration factors to translate the individual failure times to a common use condition. This provides an estimate of the distribution of failures in time. These failure distributions allow us to estimate TT1%F.

Note that TTF values are typically given at 40°C. For applications that have "room temperature" as the ambient temperature, 40°C TTF data will be extremely conservative. Some applications that have ambient temperatures above 40°C may not be operated at these elevated temperatures all the time. If the ambient temperature fluctuates during operation (e.g., 25-70°C), the effective ambient temperature over the operational life of the device will be less than the upper end of the range. In many such situations, 40°C might be a reasonably good approximation of the effective ambient temperature to be used in calculating reliability. Nevertheless, once the acceleration factors are known, the lifetime at any given temperature and current can be calculated in a straightforward manner.

4.2 Dry Pulsed Test

Pulsing may be done to achieve either higher output power at the same temperature or to maintain output power at higher temperatures. While pulsing effectively reduces the operational duty cycle, pulsing is usually done at higher currents than when using CW. How these two factors combine to impact reliability is dependent upon the specifics of each case.

4.2.1 Pulsing to Improve Output Power and Reliability

As the current to a VCSEL is increased beyond the threshold current (I_{th}), the output power increases and reaches a maximum, P_{max}, at a current that is defined as I_{max}. As the current is increased further, beyond I_{max}, the LI curve rolls over. This is rollover phenomena is caused by internal junction heating and is known as "Thermal Rollover".

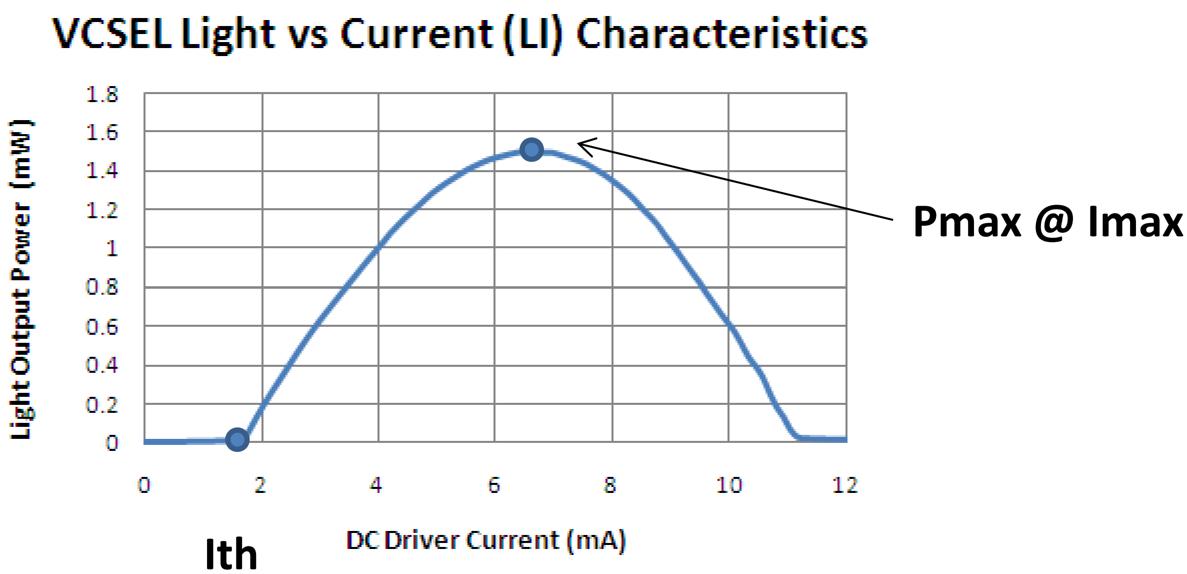

Figure 1: Typical VCSEL LI diagram

The thermal heating of the junction can be reduced by application of short current pulses at reduced duty cycle (but no change in current). The reduced junction heating results in significantly increased optical output power as compared to the CW case. If the pulse length applied to the VCSEL is shorter than the thermal time constant of the VCSEL, then the junction temperature does not rise as much during the pulse as it would if it were driven with CW current. Figure 2 shows an example of this for a Communications Grade VCSEL. (For a detailed explanation, see VIXAR Application Note "Operation of VCSELs Under Pulsed Conditions -- Increasing VCSEL Output Power" [5].)

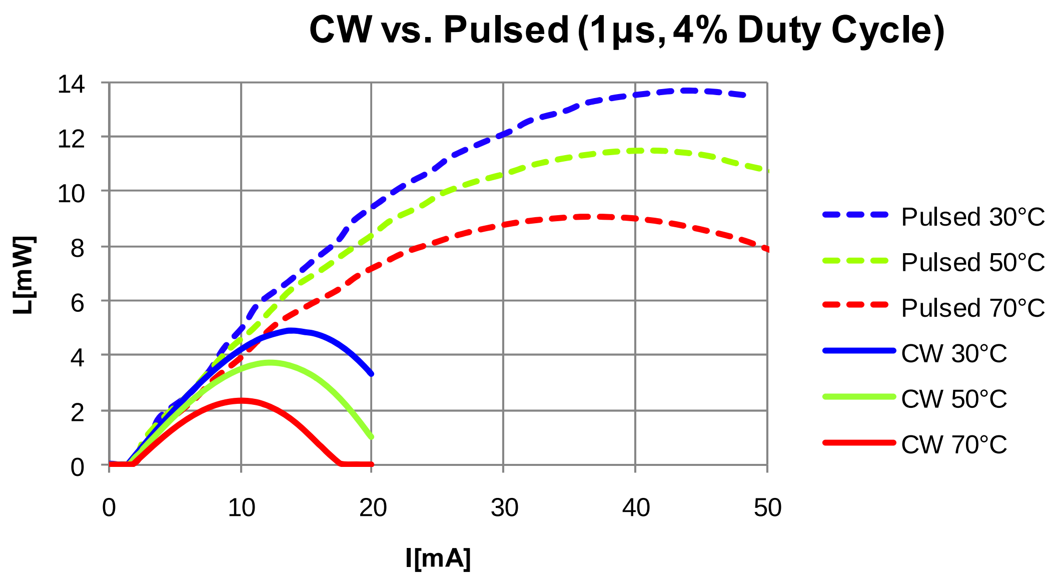

Figure 2: Increased Output Power with Pulsing

Besides providing more power at higher currents and temperatures, pulsed operation can also provide a longer VCSEL lifetime in many situations. As the "on" pulse width of the current powering the VCSEL becomes shorter and shorter the junction heating effect becomes smaller and smaller. Since the VCSEL temperature is reduced, the lifetime of the product is improved. Also, since the device is only on for a small percentage of each cycle it's effective lifetime will increase. For instance a 12.5% duty cycle should increase the lifetime by 8 times. However, if more current is required to get the desired optical power from the laser, then the lifetime will be reduced by this higher current. The gains in lifetime because of the lower temperature and reduced on time must be weighed against the losses due to the increased current.

4.2.2 Dry Pulsed Test Conditions

The table below describes the various combinations of temperature and current being used for the dry pulsed test two product families. Pulsed tests are typically done at 12.5% duty cycle and 1 µsec pulse width. Current levels are designed for the specific VCSEL type being tested.

CG Pulsed	85° C	105° C	125° C
7 mA	X		X
11 mA	X	X	X
15 mA		X	
18 mA	X	X	X

MM Pulsed	85° C	105° C	125° C
7 mA	X		X
18 mA	X	X	X
24 mA		X	
30 mA	X	X	X

Table 2: Dry Pulsed Test Conditions

4.2.3 Dry Pulsed Test Procedures

For these tests typically groups of 16 devices (a total of 144 devices) are tested under each of the conditions indicated in Table 2. They are periodically removed from the testing conditions and LIV measurements are taken at room temperature at a specified CW current.

4.2.4 Dry Pulsed Test Analysis

After analyzing the data as a function of temperature and current to determine the acceleration factors, we then perform a "meta-analysis", i.e., we use the calculated acceleration factors to translate the individual failure times to a common use condition. This provides an estimate of the distribution of failures in time.

4.3 Humidity Test

4.3.1 Humidity Test Conditions

Humidity tests are done at 85°C and 85% humidity. Testing is performed with devices that are directly exposed to the environment (non-hermetic) or devices encapsulated with a silicone compound or both. The current used for the non-hermetic testing is typically less than or equal to their normal operating current. As stated above in "Test Conditions and Procedures" the VCSEL needs to be under bias for worst case humidity testing, but using a high current heats the surrounding air and reduces the relative humidity in the environment surrounding the VCSEL. Therefore, the recommended current for humidity testing is above threshold but less than the operating temperature. [6]

4.3.2 Humidity Test Procedures

Typically 32 devices are tested. They are periodically removed from the testing conditions and LIV measurements are taken at room temperature. These tests continue for a minimum of 1000 hours.

4.3.3 Humidity Test Analysis

As is typical throughout the VCSEL industry, we do humidity testing as a qualification type of test. We expect devices to last at least 1000 hours without any failures. Most humidity failures are abrupt and not gradual like the wear out mechanism of dry accelerated aging. Devices that do fail during humidity test are sent through failure analysis to determine the root cause of failure.

5 Conclusions

Reliability testing is continuously ongoing at Vixar for all of our products. We have collected data on hundreds to thousands of devices for each product over tens of thousands of hours of accelerated temperatures and currents. These accelerated hours under test translate into millions of hours at standard use conditions. We use this data to create estimates of lifetime for each customer's specific use conditions.

Use of the appropriate VCSEL family (i.e., SM, MM, or CG) will result in optimal reliability while still meeting the other requirements of the application (ambient temperature, output power, beam shape, wavelength, etc.). When higher reliability, higher output power, or higher use temperature is needed for any VCSEL family, pulsed mode operation offers a possible solution.

6 References

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