

Reliability Assessment of VCSEL Devices for 5 Gbit/s Data Transmission in Automotive Environments

Optical data transmission with data rates of up to 150 Mbit/s in automotive environments is realized today by using LED/RCLED transmitter devices. This article discusses a reliability assessment process for

VCSEL semiconductor devices by means of established reliability methods to demonstrate the robustness under the demanding requirements. The assessment is based on the semiconductor device itself without regards to the packaging.

By Jörg Angstenberger and Dr. Viktor Tiederle

Due to the fact that LED/PMMA-based transmission layers have a limited bandwidth of about 100 up to 200 Mbit/s, there is a demand to change some key devices in the optical physical layer to achieve higher data rates. In terms of the transmitter, vertically emitting laser diodes (VCSEL, vertical cavity surface emitting diodes) could be the choice to provide bandwidth in the range of several Gbit/s for future optical automotive networks. VCSEL devices are well established. They are reliable in short-link datacom applications such as Gigabit Ethernet. However, there is no reliable data about the robustness of VCSEL devices in automotive environments.

Description of automotive environmental requirements

First, the environmental requirements and reliability goals of semiconductor devices in automotive applications have to be defined. By knowing the

thermal distribution of the compartment area in the car, a temperature model can be developed and the thermal requirements of the VCSEL in the application can be derived. The mission profile is principally defined by the required life time of the device in a specific compartment area of the vehicle. In terms of motor vehicles made by important German manufacturers, this information can be found in the LV124 specification [1] published by Audi, BMW, Daimler, Porsche and Volkswagen. Figure 1 shows the failure rate of an electronic semiconductor device dependent on life time and the relationship to a defined car mission profile [2].

To assure that the electronic device is able to fulfill the mission profile of the car,

the failure rate of the device has to be below the maximum accepted failure rate over the defined car life time. The required car life time is specified with 8,000 h according to LV124. With this consequence, the potentially high failure rates in the early life of the device have to be reduced by a production measure such as burn-in. In addition, the beginning of the wear-out phase has to be far beyond the end of the defined car life time. There is no general definition of a maximum accepted failure rate during the life of a car in the automotive area. Nevertheless, for a less complex automotive semiconductor device, random failure rates of ≤ 10 FIT are assumed and accepted. Therefore, to demonstrate that a VCSEL device is able to meet the reliability of a standard automotive semiconductor, a test setup is sought that proves this magnitude over the defined car life time with a confidence level of generally 90 percent.

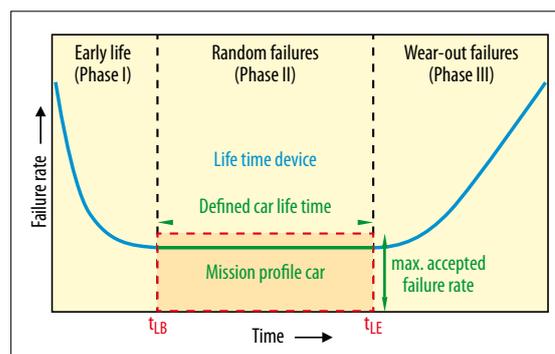


Figure 1. Mission profile of a car and life time chart of an electronic device.

Required temperature conditions

According to LV124 there are certain temperature profiles corresponding to different compartment areas in the car. In the case of MOST applications, only temperature profiles 1 and 2 are relevant. Considering the worst-case application condition, the further study will be focused only on temperature profile 2 (Table).

Figure 2 shows the thermal model of a VCSEL device packaged and mounted within an electronic control unit (ECU) in the compartment area. The relevant temperature for the reliability assessment is the same as the junction temperature of the VCSEL device. The junction temperature depends on the ambient temperature – out of the related temperature profile of the compartment area – and the thermal resistance between the ambient tempera-

Temperature Profile 1 in °C	Temperature Profile 2 in °C	Percentage	Operating hours
-40	-40	6	480
23	23	20	1,600
40	50	65	5,200
75	100	8	640
80	105	1	80
Operating hours complete:			8,000 h

Table. Temperature profiles according to LV124.

ture and the junction temperature. The resulting thermal resistor is defined by the thermal model of the VCSEL itself; the thermal resistance of the packaging and the temperature increase between the surface of the VCSEL packaging and the ambient temperature of the compartment area.

Derived operating conditions

Because the reliability assessment is performed on the bare VCSEL semiconductor, and the thermal resistance between the substrate of the VCSEL and the ambient temperature has not been known yet, a worst case temperature increase of 5 K between ambient and the substrate of the VCSEL was assumed for temperature profile 2. This results in a substrate temperature profile at the VCSEL with a maximum temperature of 110°C. For this reason, the junction temperature of the VCSEL is dependent on

the maximum substrate temperature and the power dissipation of the VCSEL. This is fixed by the individual thermal model of each VCSEL device. The power dissipation is related to the operating current and has an assumed value of about 5 mA (typical).

Reliability assessment

In this reliability assessment, there are basically two intentions in performing life time testing:

- To determine the point in time when the wear-out phase of the device begins and
- to predict the random failure rate of the device during the specified car life time.

In this case, the scope of the reliability validation is related to the bare VCSEL chip without packaging and connections. So the life time test is focused only on the failure mechanisms that are activated by thermal stress. Therefore, testing is done by using a high temperature operating life test setup (HTOL). During the test, the VCSEL devices are in an active mode that is comparable with real operation, for instance similar power dissipation.

To ensure that all possible failure mechanisms are addressed by the test setup, the junction temperature of the VCSEL under test conditions has to coincide with the maximum possible junction temperature of the corresponding temperature profile of the compartment area at least. The maximum test temperature is limited by the maximum junction temperature of the VCSEL device and is specified by the thermal model of each individual VCSEL.

Life time testing in order to predict low random failure rates and late wear-out behaviour is very time consuming. Because the life time of an electronic device generally decreases over an increase of operating temperature, there is a possibility of accelerating the test

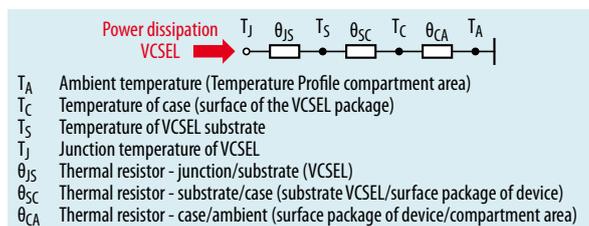


Figure 2. Thermal model.

$$A_f = \left(\frac{I_1}{I_2}\right)^N \times e^{-\frac{E_A}{k} \left(\frac{1}{273,15^\circ\text{C} + T_1} - \frac{1}{273,15^\circ\text{C} + T_2}\right)}$$

E_A Activation energy
 k Boltzmann constant
 A_f Acceleration factor
 I₁ Current at test
 I₂ Operating current
 T₁ Test temperature (junction temperature T_J)
 T₂ Temperature in operating condition (junction temperature T_J)
 N Current acceleration exponent

Equation 1. Modified Arrhenius.

under certain conditions by increasing the junction temperature in addition. This behaviour is described by the modified acceleration model of Arrhenius (Equation 1) and by the Telcordia GR-468-CORE [3].

Obtaining wear-out and random failure rate information from one single test setup is challenging. On the one hand, a significant acceleration by increasing the temperature and operating current is necessary to achieve an acceptable test time for wear-out. On the other, this high acceleration increases the risk of activating additional random failure mechanisms that increase the random failure rate. Therefore, the life test is divided into two different setups:

- Determining the point of time for wear-out and
- the prediction of random failures.

Test setup for wear-out

Wear-out failures are generated by using a limited number of samples and performing a high-temperature operating life test with a large acceleration factor. Equation 1 demonstrates that a high acceleration factor can be achieved by increasing the test temperature and the test current beyond the maximum specified application conditions. According to Telcordia GR-468-CORE, the current acceleration exponent and the activation energy can be derived empirically out of aging tests. A typical value for wear-out activation energy is 0.7 eV and for the current acceleration exponent N = 2. The intent of this test is to generate a significant number of failures, for example 50 per cent, in a limited time frame.

Figure 3 shows a typical reliability wear-out plot in test conditions for a dummy device. The blue graph is the fitted probability of failure;

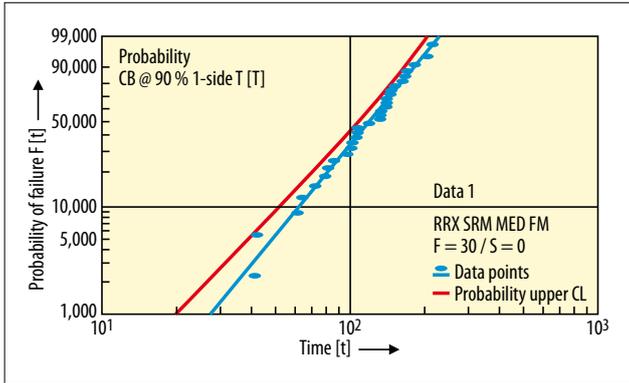


Figure 3. Typical wear-out chart.

the red graph is the lower single-sided 90 per cent confidence level of the test data.

In this case, one per cent of the devices are expected to fail in test conditions by wear-out mechanisms after 20,000 h with a confidence level of 90 per cent. To get a prediction of the wear-out behaviour at the regular application condition (lower temperature and current), the graph can be transformed by using the Model of Arrhenius. This results in a parallel right-shift of the graph on the x-axis.

According to LV124, the required life time of electronic devices should be at least 8,000 h considering the specified temperature profile. Therefore, the test has to prove that the wear-out point with failure rates which are significantly higher than the specified 10 FIT, is far off the 8,000 h.

Test setup random failures

In comparison to the test setup for wear-out failure mechanisms used to generate a significant number of failures in an acceptable time frame, the test setup for random failure mechanisms tends to generate a large number of device hours.

To assure that all inherent failure mechanisms are activated, the test tem-

$$D(T_{JApp}) = nt \times e^{-\frac{E_A}{k} \left(\frac{1}{273,15^\circ C + T_{JTest}} - \frac{1}{273,15^\circ C + T_{JApp}} \right)}$$

$D(T_{JApp})$	Device hours at application condition
n	Number of tested devices
t	Number of test hours at test condition T_{JTest}
T_{JTest}	Temperature test condition (junction temperature)
T_{JApp}	Temperature application condition (junction temperature)
E_A	Activation energy
k	Boltzmann constant

Equation 2. Calculation of device hours at application condition.

perature of the junction has at least to coincide with the maximum junction temperature of the real application. In order to avoid the risk of activating additional failure mechanisms that could be addressed by an additional temperature increase over the specified operating conditions, the acceleration factor for random failure testing is

kept at a moderate level and depends on the thermal model of each individual VCSEL design.

In Equation 2 you can see how to calculate the number of device hours within a certain segment of the application temperature profile regarding a number of tested devices and the test duration. The equation is based on the Model of Arrhenius considering a conservative approach according to Telcordia GR-468-CORE; the activation energy is set to 0.35 eV without using an additional current acceleration.

The corresponding random failure rate of a certain application condition

$$\lambda(T_{JApp}) \leq \frac{X^2(CL, 2r + 2)}{2D(T_{JApp})}$$

$\lambda(T_{JApp})$	approved random failure rate for corresponding application condition
T_{JApp}	Junction temperature (application condition)
$D(T_{JApp})$	Tested device hours at application condition T_{JApp}
CL	Confidence level
r	Number of failures
$X^2(CL, 2r + 2)$	Bound of X^2 distribution

Equation 3. Random failure rate.

and a certain confidence level is calculated according to Equation 3:

To predict a failure rate not only for a certain temperature but for the complete specified temperature profile according to LV124, the random failure rate is calculated for each temperature segment separately. Afterwards, the failure rate of each temperature segment is weighted by the individual percentage of this segment. Finally, the weighted failure rate of each segment is added to obtain the random failure rate for the complete temperature distribution. According to the defined requirements, the test setup has to be able to prove a random failure rate of about 10 FIT with a confidence level of 90 per cent.

Future perspective

In 2012 a reliability study based on the introduced evaluation method was realized on three VCSEL devices by different manufacturers. The selected devices fulfill the basic functional requirements of a potential further optical MOST Physical Layer. Initial test results furnish proof that the requirement of an 8,000 h life time can be achieved without running into wear-out. There are also some initial test results that demonstrate that a random failure rate of around 10 FIT is realistic and feasible. Some tests are still running and planned to be finished by the middle of 2013.

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References

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- [3] GR-468-CORE Issue 2. Generic Reliability Assurance Requirements for Optoelectronic Devices Used in Telecommunications Equipment. s.l. : Telcordia Technologies, September 2004.



Dipl.-Ing. (FH)

Jörg Angstenberger

works at Ruetz System Solutions as an expert for reliability and functionality of MOST Physical Layer components. He has improved the reliability of

electronic devices in the automotive area for more than 10 years and is responsible for the Technology Assessment and the MOST Compliance Test of the Full Physical Layer.

joerg.angstenberger@ruetz-system-solutions.com



Dr. Viktor Tiederle

acts as Senior Consultant and President of Relnetyx AG. He has gained experience in the area of quality, reliability, and validation of electronic products for many years. He has

worked with MOST technology since 2001. He mainly deals with the MOST full physical layer for single components such as FOT and pigtail.

viktor.tiederle@relnetyx.com