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Degradation Characteristics and Reliability Assessment of 1310 nm VCSEL for Microwave Photonic Link

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Abstract: The long-term reliability of the commercially available vertical-cavity surface-emitting laser (VCSEL) at 1310 nm wavelength is investigated. To do so, a high current accelerated life test is used to evaluate the 1310 nm VCSEL reliability. Variations of properties that depend on the operating condition are characterized by the light-current-voltage, leakage current and low-frequency noise. When the aging current is 6 mA, 8 mA and 10 mA, the maximum output power reduces by 5%, 6% and 15% of the initial value, respectively. It is demonstrated theoretically and experimentally that the leakage current increases and reverse bias breakdown voltage decreases after the accelerated current aging test. The current noise power spectral density increases after the device ages, and the noise increases with the augment of the electrical stress. When the bias current of VCSEL is below the threshold, the frequency index factor and noise amplitude gradually increase with the bias current increase. Further, lifetime fitting curves of the devices at an accelerating current of 6 mA, 8 mA and 10 mA are obtained, and the median lifetime of 67 years at the operating current is extrapolated.

Keywords: vertical-cavity surface-emitting lasers; accelerated life test; light-current-voltage; leakage current; low-frequency noise; reliability assessment



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1. Introduction

The vertical-cavity surface-emitting laser (VCSEL) proved to be a powerful competitor to the edge-emitting semiconductor laser owing to the circular output beam, low threshold current, low cost, high-speed modulation and easy fabrication in two-dimensional arrays [1–4]. These characteristics enabled it to be extensively applied to microwave photonic links, short-distance optical interconnections, laser radar and chip-scale atomic clocks [5–10]. Nowadays, VCSELs emitting at various wavelengths are extensively researched, and some of them, such as 850 nm, 940 nm and 650 nm devices, are commercialized [11–13]. VCSELs emitting at 1310 nm have broad application prospects in microwave photonic links. Opto-electronic oscillators based on VCSELs can generate a stable microwave signal with low phase noise. With the wide application of VCSEL, the reliability requirement is becoming higher. In order to improve VCSEL's long-term stability, one has studied the degradation characteristics and reliability assessment of VCSELs. In 2003, Agilent Technologies investigated the reliability and failure mechanism of oxide VCSELs in non-hermetic environments. Three failure modes of oxide VCSELs at biased 85/85 testing are identified, and dislocation growth is the most common [14]. In the same year, Joachim J. Krueger et al. found that the aperture size is the main parameter determining the device's ESD tolerance and reveals a characteristic defect structure around the tip of the oxide layer that is responsible for the creation of dislocation networks in the active region causing the device to fail rather

rapidly [15]. In 2007, Keun Ho Rhew et al. investigated the reliability of 1550 nm VCSELs. The computed activation energy for the 1550 nm VCSEL failure mechanism was about 0.79 eV and the extrapolated median VCSEL lifetime at room temperature was about 2×10^7 h [16]. In 2009, 850 nm VCSELs had a wearout lifetime of over 24 years with less than a 1% failure rate at 70 °C operating conditions [17]. In 2013, Robert W. Herrick et al. showed the mechanism for corrosion failure in oxide aperture VCSELs. Cracks near the tip of the oxide aperture cause the line dislocations, which, in turn, cause the growth of climb dislocations (DLDs) in the active region [18]. In 2019, A. W. Bushmaker et al. presented a hypothesis attributing the location of the defects around the oxide aperture edge to current crowding in that area, which increases local electrical and thermal stress [19]. In 2021, reverse-biased emission microscopy was employed to investigate a high-power VCSEL array at a non-degraded state and after high electrical stress. It has been found that degraded arrays exhibit more intense electroluminescence in areas with faulty emitters containing dark line defects in the active area [20]. The reliability of 1310 nm VCSEL has become a common problem that manufacturers and users are concerned about and need to solve urgently. In 2003, the reliability for 1.3 micron VCSELs with InGaAsN quantum well active layers was demonstrated, and a median life of 135 years at typical operating conditions was predicted [21]. In 2013, the reliability data of wafer-fused VCSELs was presented, and at 9 mA and 8 mA, the driving current evaluation of the time to 1% failure at 70 °C resulted in 18 years and 30 years, respectively [22]. There are relatively few studies on the failure mechanism and reliability of a 1310 nm VCSEL at home and abroad.

In this paper, the long-term reliability of all monolithic 1310 nm VCSELs is investigated. High current accelerated life tests are used to evaluate the 1310 nm VCSEL reliability. Variations of the properties that depend on the operating condition are characterized, and the device's median lifetime is extrapolated.

2. Device Structure and Reliability Testing

In the following section, the 1310 nm VCSELs performance characterization and reliability assessment as a commercial device are discussed, and the schematic of the structure is shown in Figure 1. The epitaxial wafer is grown on an N-type InP substrate. The oxidation layer in the N-DBR contains a high Al concentration, providing current confinement and index guiding for the VCSEL, and the P-DBR consists of a multilayer dielectric layer. The VCSEL chips are packaged in TO46 headers.

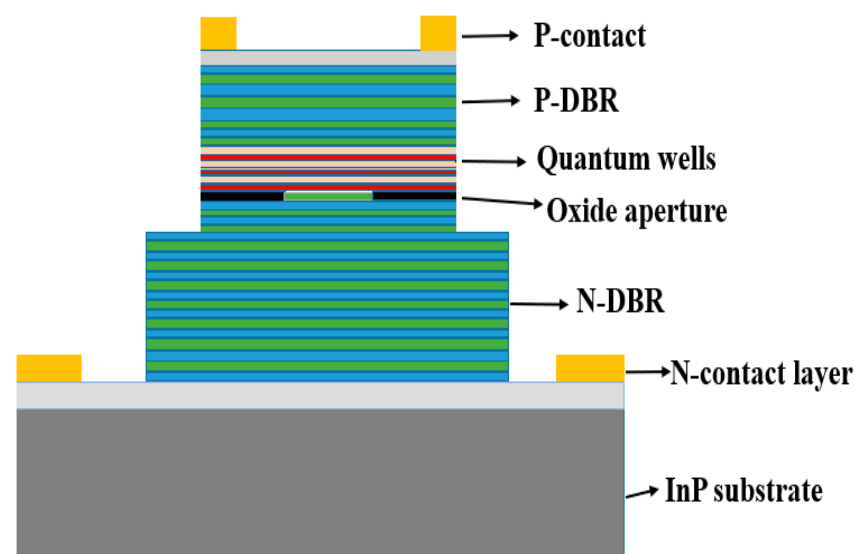


Figure 1. Schematic of the 1310 nm VCSEL device.

The device is installed on the fixture of the aging system, and the built-in current source of the system generates constant and varying currents. When the current is greater

than the threshold current of the device, the output power of the device is received by the photodetector integrated into the fixture, and the measured data is exported to the software system. The device current is continuously adjusted by the integrated software, and the output power is also continuously changed. Through the long-term recording of test data by the operating system, and analyzing the L-I-V curve, the variation trend of the output power with the current can be obtained.

The accelerated life tests for 1310 nm VCSELs are performed with an aging current of 6 mA, 8 mA and 10 mA at an ambient temperature of 35 °C. There are three samples for each current stress condition, and the conditions are summarized in Table 1. Before the aging test, the L-I-V measurement is performed for each VCSEL with the test current up to 10 mA. Then, the devices are returned to the aging test current. After the aging test, the L-I-V curve is tested again. The failure criterion is defined as a plus or minus 20% change in the output power compared with the optical power measured at the beginning of the aging test at a fixed bias current.

Table 1. Test conditions.

Temperature (°C)	Aging Current (mA)	Number of Samples
35	6	3
35	8	3
35	10	3

3. Discussions

3.1. LIV Characterization

The accelerated life tests are performed to investigate the VCSELs degradation with electrical stress, and a typical sample is selected for analysis under each set of stresses. Variations of power and voltage with current at different electric stress are shown in Figure 2, indicating the light-current-voltage (L-I-V) curves of VCSELs with accelerated aging current at 6 mA, 8 mA and 10 mA, respectively. The black line represents the LIV curves before accelerated aging, and the red line represents the LIV curves after aging. As can be seen, the maximum output power of the device is 0.82 mW and 0.78 mW before and after aging at 6 mA, and the power is reduced by 5% of the initial value. At an electric stress of 8 mA, the maximum output power of the device is 0.68 mW and 0.64 mW before and after aging, and the power is reduced by 6% of the initial value. At an electric stress of 10 mA, the maximum output power of the device is 0.79 mW and 0.67 mW before and after aging, and the power is reduced by 15% of the initial value. The power saturation currents and V-I curves are basically unchanged, and the error for all measured values is less than 0.01 mW.

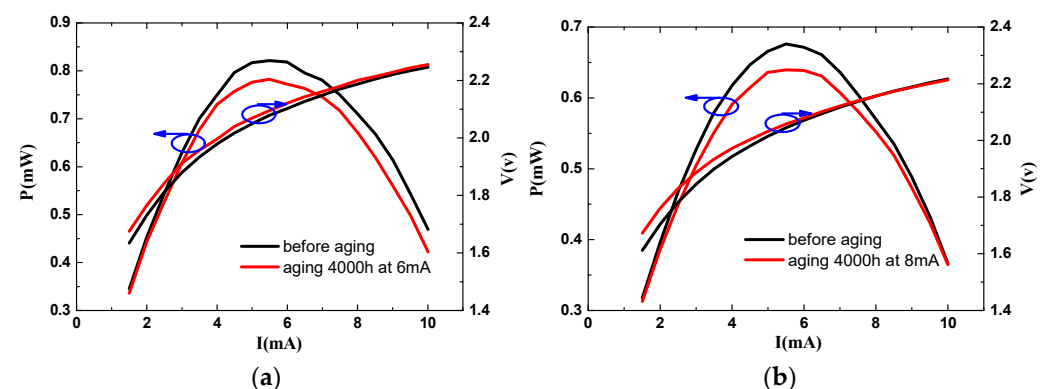


Figure 2. Cont.

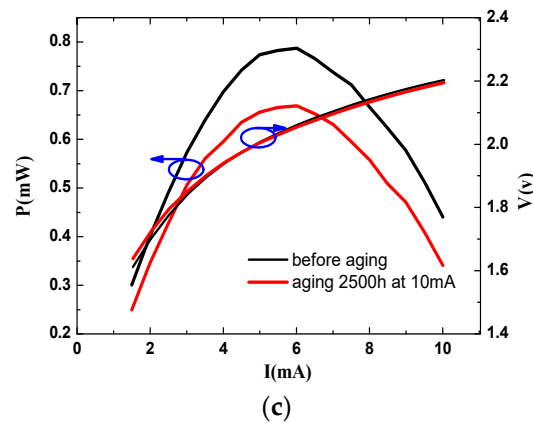


Figure 2. Optical output power versus drive current from a device before and after aging at (a) 6 mA, (b) 8 mA and (c) 10 mA, respectively.

3.2. Leakage Current Characterization

By monitoring reverse leakage, an early indication of device reliability can be attained. The measured leakage current characteristics of the 1310 nm VCSELs before and after aging are graphed in Figure 3. We observe that the leakage current increases and reverse bias breakdown voltage decreases after the accelerated current aging test. The increase in leakage current can be explained by the tunneling mechanism. The long-term current stress increases the temperature of the active region, and the carriers originating from thermal excitation at high temperatures cause an increase in the tunneling dislocations. It is easier for the carriers to escape the restriction of the quantum barrier, resulting in an increase in the leakage current. The reverse voltage reflects the number of defects in the active region of VCSEL. Non-radiative recombination will be introduced because of lattice defects, and the energy will be transmitted to other charged particles and phonons, which results in Auger recombination and lattice vibration. The vibration will promote the slip of defects, thus leading to defect enhancement and reverse voltage reduction.

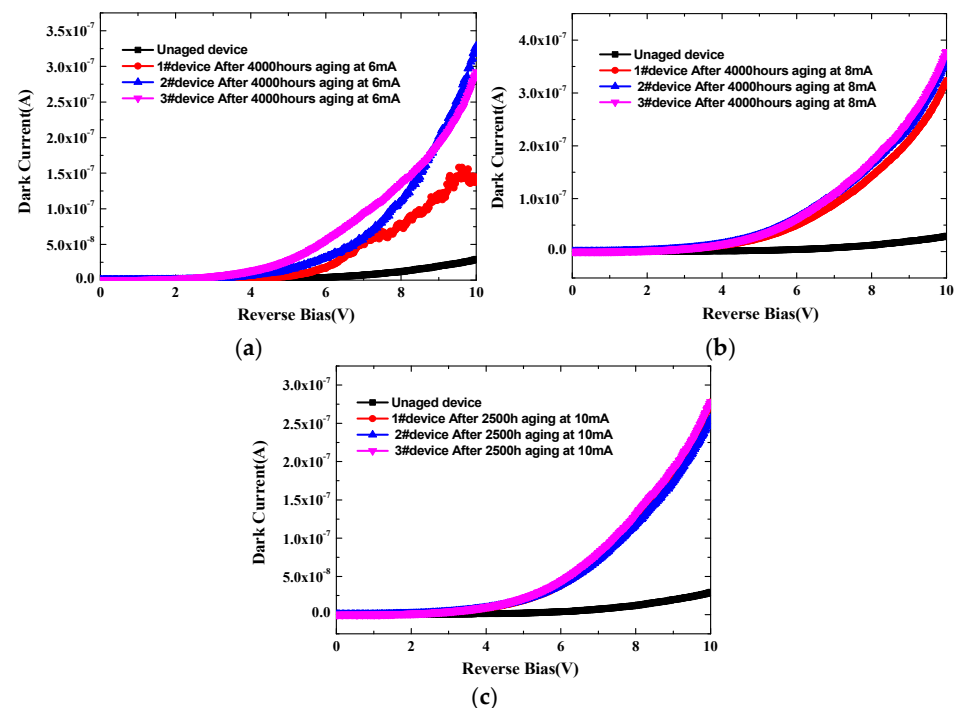


Figure 3. Reverse biased leakage current curves of the devices before and after aging at different bias currents, (a) 6 mA, (b) 8 mA and (c) 10 mA.

3.3. Low-Frequency Noise Characterization

Measurements of the low-frequency noise (LFN) are vitally sensitive to some of the microscopic processes that could indicate impending failure. The internal defects, surface leakage and bad ohmic contact of the semiconductor laser will increase the LFN, so the noise can be used to reflect the reliability of 1310 nm VCSEL.

The 1/F noise power spectral density of the surface non-radiative recombination current can be expressed as:

$$S_{I_{nr}} = I_{nr}^2 \left(\frac{q}{k_0 T} \times \frac{1}{AN_{ot}} \right)^2 S_{N_{ot}}(f), \quad (1)$$

where I_{nr} is the non-radiative recombination current, q is the electron charge, k_0 is the Boltzmann constant, T is the degree Kelvin, A is the cross-sectional area of the PN junction, N_{ot} is the number of oxide trap charges and $S_{N_{ot}}(f)$ is the oxide trap charge density. $S_{N_{ot}}(f)$ can be expressed as:

$$S_{N_{ot}}(f) = \frac{q^2 k_0 T N_t \lambda}{f}, \quad (2)$$

where N_t is the effective body defect density, λ is the attenuation tunneling distance. According to the mobility fluctuation model [23], when the VCSEL is below the threshold current, the 1/F noise caused by the surface non-radiative recombination current can be expressed as:

$$S_{I_{nr}}(f) = I_{nr}^2 \frac{q^4 N_t \lambda}{k_0 T A^2 N_{ot}^2 f}. \quad (3)$$

According to the above 1/F noise model, the 1/F noise of VCSEL with a small injection current is generated by the fluctuation of surface non-radiative recombination current, which depends on the surface oxide trap density and lattice dislocation. At the same time, the defects, impurities, and dislocations of VCSEL form a surface non-radiative recombination current. Therefore, the reliability of VCSEL can be evaluated by measuring the 1/F noise of the device under operating conditions below the threshold current.

In order to analyze the dependence of LFN on bias currents below the threshold, a typical sample is selected for analysis under each set of aging stresses. The current noise power spectral density versus frequency at different bias currents are shown in Figure 4. It can be seen from the figure that current noise power spectral density decreases with the increasing frequency, indicating that the current noise of the 1310 nm VCSEL is mainly the 1/F noise in the low-frequency band. Meanwhile, the frequency index factor and noise amplitude gradually increase with the bias current increase from 0.001 mA to 0.5 mA, as shown in Table 2.

Table 2. The frequency index factor and noise amplitude at different bias currents.

Bias Current (mA)	6 mA		8 mA		10 mA	
	Frequency Index Factor γ	Noise Amplitude at 1 Hz (A^2/Hz)	Frequency Index Factor γ	Noise Amplitude at 1 Hz (A^2/Hz)	Frequency Index Factor γ	Noise Amplitude at 1 Hz (A^2/Hz)
0.001	0.8	1.74×10^{-20}	0.83	6.64×10^{-21}	0.8	5.05×10^{-21}
0.1	0.9	1.13×10^{-17}	1	1.16×10^{-17}	1.08	6.51×10^{-17}
0.3	0.98	6.9×10^{-17}	1.03	4.31×10^{-17}	1.25	1.31×10^{-15}
0.5	1.05	6.89×10^{-17}	1.05	2.72×10^{-16}	1.28	4.32×10^{-15}

At operation current, the measured low-frequency noise behaviors of the 1310 nm VCSELs before and after aging are graphed in Figure 5. It indicates that the current noise power spectral density increases after the device aging, and the noise increases with the augment of the electrical stress. After 2500 h aging of the device at 10 mA, the noise power spectral density is one order of magnitude higher than the device before aging. The result

indicates that with the increase of electrical stress, the active region dislocation and oxide layer defects of the device increase, and the performance degradation becomes more serious.

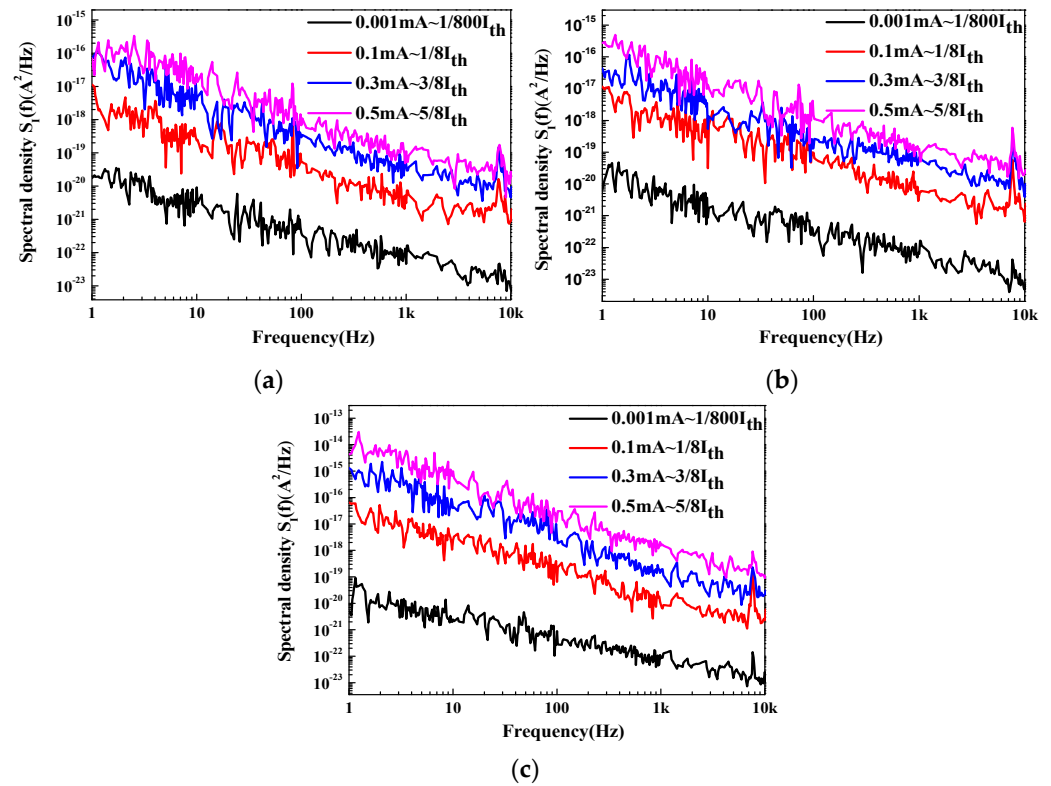


Figure 4. The current noise power spectral density curve of VCSELs versus frequency for different bias currents, (a) after 4000 h aging at 6 mA, (b) after 4000 h aging at 8 mA and (c) after 2500 h aging at 10 mA.

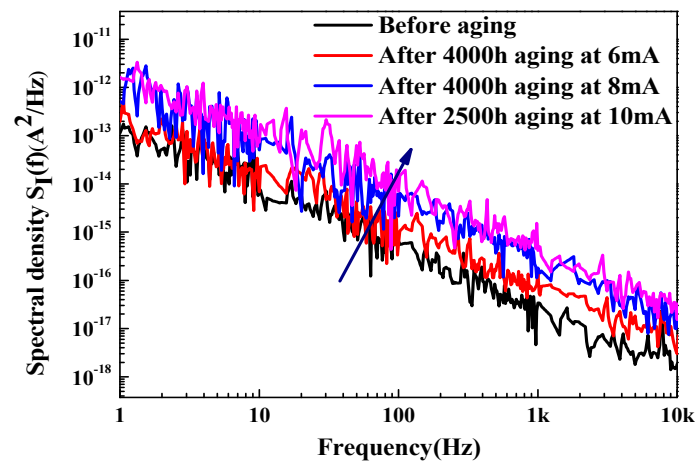


Figure 5. The current noise power spectral density curve of the VCSEL before and after aging.

4. Results

The semiconductor laser-accelerated aging test with the electric stress can be described by the inverse power law, as shown in Equation (4).

$$T = Av^{-c} \quad (4)$$

where T is the lifetime, A is the constant, v is the electric stress, c is a constant related to activation energy. Variations of the output power degradation rates with the aging

time at different electric stresses are shown in Figure 6. As can be seen from the figure, when the aging current at 6 mA, 8 mA and 10 mA, the rate of change in the output power increased linearly with the aging time. In addition, as the electric stress increased, the power degradation rate became faster.

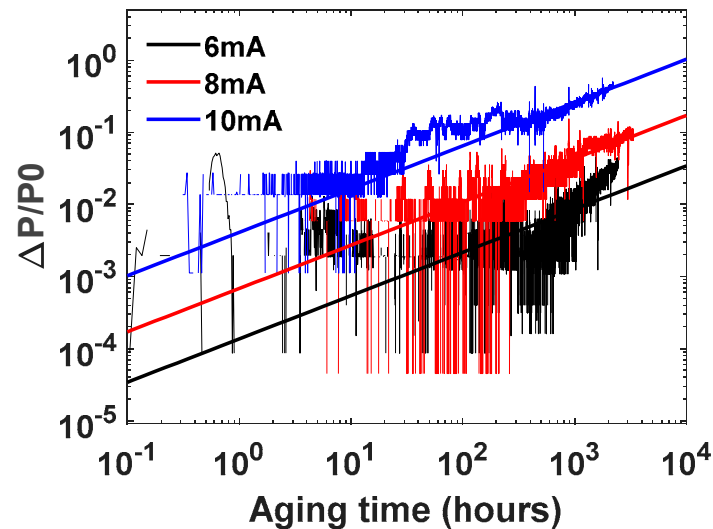


Figure 6. The rate of change in output power varies with the aging time at different electric stress.

The mathematical relationships between output power degradation rates and aging time at 6 mA, 8 mA and 10 mA are fitted to Equations (5) to (7), respectively. According to Equations (5) to (7), the lifetime of devices at different currents can be calculated. Using the lifetime at different currents to make linear regression of the inverse power law, the linear change of lifetime with current is obtained, as shown in Figure 7. Then, Formula (8) of the device lifetime and the current is obtained, where τ is the lifetime, I is the magnitude of the electric stress and the unit is mA. By processing the test data, the lifetime of the device at 5.5 mA operating current is predicted to be 67 years.

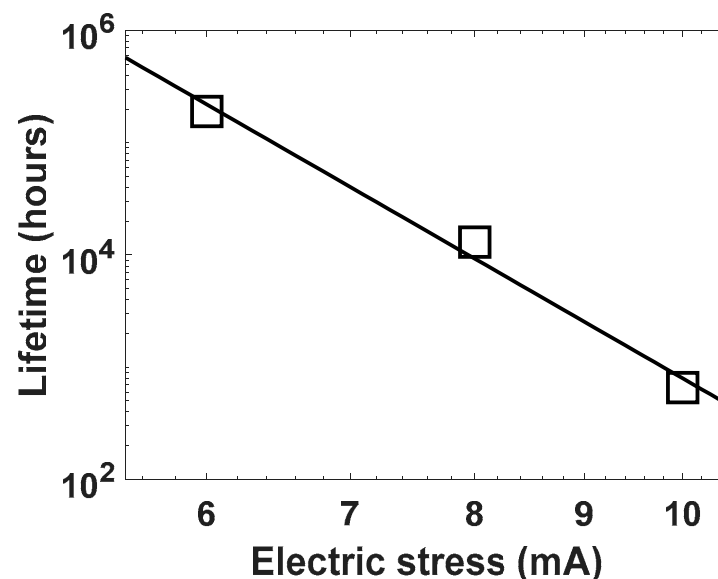


Figure 7. Variation of device life with electrical stress.

Accelerated life testing can be used to quickly obtain the reliability and lifetime distribution of the device. This method is faster and cheaper than aging under normal operating conditions, and aging under normal operating conditions is not feasible because

of the long lifetime. However, the reliability assessment technique is a statistical method that has certain differences for a single device. Besides, the technique is not suitable for the devices with changing operating conditions, such as intermittent life evaluation of power devices.

$$\frac{\Delta P}{P_0} = 1.36 \times 10^{-4} \cdot t^{0.6} \quad (5)$$

$$\frac{\Delta P}{P_0} = 6.80 \times 10^{-4} \cdot t^{0.6} \quad (6)$$

$$\frac{\Delta P}{P_0} = 4.08 \times 10^{-3} \cdot t^{0.6} \quad (7)$$

$$\tau = 8.2 \times 10^{13} \cdot I^{-11} \quad (8)$$

5. Conclusions

In this work, the degradation characteristics and lifetime evaluation of the 1310 nm VCSEL are demonstrated. When the electrical stress is 6 mA, 8 mA and 10 mA, the maximum output power reduces by 5%, 6% and 15% of the initial value, respectively. We find that leakage current increases and reverse bias breakdown voltage decreases after the accelerated current aging test, and the increase in leakage current is explained by the tunneling mechanism. The current noise power spectral density, the frequency index factor and noise amplitude gradually increase with bias current increase from 0.001 mA to 0.5 mA. Meanwhile, the current noise power spectral density increases after the device aging, and the noise increases with the augment of the electrical stress. The result indicates that with the increase of the electrical stress, the active region dislocation and oxide layer defects of the device increase. In addition, lifetime fitting curves of the devices at accelerating current of 6 mA, 8 mA and 10 mA are obtained, and the median lifetime of 67 years at operating current is extrapolated. This technique can also be used in degradation characterization and lifetime evaluation of 1550 nm VCSEL, which is of great significance for the reliability assessment of optical communication devices.

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