Reliability assessment of 1.55-μm vertical cavity surface emitting lasers with tunnel junction using high-temperature aging tests

Keun Ho Rhew a, Su Chang Jeon a, Dae Hee Lee b, Byueng-Su Yoo b, Ilgu Yun a,*

a Semiconductor Engineering Laboratory, Department of Electrical and Electronic Engineering, Yonsei University, 134, Shinchon-Dong, Seodaemun-Ku, Seoul 120-749, Republic of Korea
b Raycan Co. Ltd., KT Center 2F, 138 Gajeong-Dong, Yuseong-Ku, Daejeon 305-333, Republic of Korea

Abstract

In this paper, the long-term reliability of all monolithic 1.55-μm etched-mesa vertical cavity surface emitting lasers (VCSELs) with tunnel junction is investigated via high-temperature storage tests and accelerated life tests. Characteristic variations depend on the operating conditions are examined via the threshold current, the optical output power, and the dark current. The median device lifetime is extrapolated and the activation energy of the VCSELs is calculated based on the reliability testing results. In addition, the degradation mechanism of the tested VCSELs is analyzed using the correlation between the current–voltage characteristics ($I–V$) and the device lifetime. From these results, the long-term reliability of the VCSEL test structures for high-speed optical communication systems can be determined and the device parameters, such as dark current, can be used as a monitoring factor for estimating reliability of the VCSELs.

1. Introduction

Vertical cavity surface emitting laser (VCSEL) is a very critical component as an optical source for a high-speed optical network system owing to their many benefits such as low operating current, low cost, high-speed modulation, low-power consumption, on-wafer testing, and ease of integration. Despite more complicate fabrication compared to 850-nm wavelength VCSELs, the 1.55-μm VCSELs with various structures and material have been developed with the improvement of VCSEL technologies in recent years [1–5]. As a result, the commercialization of 1.55-μm VCSELs is currently on-going process. Therefore, the long-term VCSEL reliability is very important for commercialization since the degradation or the failure of the optoelectronic devices in the optical communication system causes many serious problems such as the noise of data, distortion, and time-delay resulting in even the failure of the system.

Various reports on the reliability of VCSELs have been published by the several researchers. Suning et al. investigated the failure mode of oxide VCSELs in the high humidity and temperature [6]. Takeshita et al. researched the degradation behavior of air-post guide VCSELs [7]. Herrick et al. studied the gradual degradation for the reliability of proton implanted VCSELs [8]. However, the reliability of all monolithic 1.55-μm etched-mesa VCSEL with tunnel junction has not been reported yet [9].

This paper presents the proposed reliability testing and analysis scheme of all monolithic 1.55-μm etched-mesa VCSEL with tunnel junction grown by metal–organic chemical vapor deposition (MOCVD). Especially, the tunnel junction is applied for reducing free carrier absorption. The high-temperature storage tests (HTSTs) and the accelerated life tests (ALTs) are performed by monitoring the dark current, the threshold current and the optical output power. The activation energy of the degradation mechanism and the median VCSEL operating lifetime at the room-temperature are estimated. The analysis on the failure mechanism according to degradation modes is conducted. In addition, the correlation between the current–voltage ($I–V$) characteristics and the device lifetime is also investigated.

2. Device structure and fabrication processes

The microscopic image and the cross-sectional view of the test VCSEL structures are shown in Fig. 1. All layers of 1.55-μm VCSELs were monolithically grown by vertical-flow low-pressure MOCVD technique on InP substrate. The 0.5-μm thick active region between two n-InP layers consists of seven strain compensated InAlGaAs quantum wells (QW). The structure consisting of a double intra-cavity contact with the 2.0-μm thick n-InP cladding layers allows high efficient heat spreading and low series resistance to overcome inherent low thermal conductivity and high voltage drop in...
quaternary distributed Bragg reflectors (DBRs). The C-doped InAlAs tunnel junction was positioned between the top n-InP layer and active region at a standing-wave node of the cavity mode. The top and the bottom mirrors were grown as undoped InAlAs/InAlGaAs DBRs. This resulted in the reduced free carrier absorption loss. The two-step mesas for the double intra-cavity contact structure were sequentially formed by reactive ion etching with mixed gases of Ar–Cl$_2$ and CH$_4$–H$_2$. Current confinement is provided by an air-gap aperture formed in the selectively wet etched 0.5-µm thick InAlGaAs active layer. AuGe/Ni/Au was used for contact metallization [10].

3. Reliability testing

The high-temperature storage tests and the accelerated life tests for VCSELs were performed at the two different ambient temperature levels of 200 °C and 250 °C. Especially, the operating current of 11 mA was used for the accelerated life tests. The test conditions are summarized in the Table 1.

![Fig. 1. (a) Microscopic image (200×), and (b) cross-sectional schematic for the test VCSEL structure.](image)

<table>
<thead>
<tr>
<th>Test temperature (°C)</th>
<th>Operating current (mA)</th>
<th># Of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>11</td>
<td>7</td>
</tr>
<tr>
<td>250</td>
<td>11</td>
<td>8</td>
</tr>
</tbody>
</table>

The schematic of the test environment is shown in Fig. 2. The test VCSELs were placed in the dry oven at the each temperature. A constant operating current that is set by Keithley 236 source measure unit (SMU) applied to each VCSEL (see Fig. 2a). The failure rate under bias conditions, the failure activation energy and the median lifetime for the device are derived from Arrhenius model [11]:

$$R = R_0 \times \exp\left(-\frac{E_a}{kT}\right)$$

where $R_0$ is a temperature-independent pre-exponential failure acceleration factor, $E_a$ is the activation energy, $T$ is the absolute temperature and $k$ is the Boltzmann’s constant. The characteristic changes of the test sample was examined via monitoring the value of voltage at given bias conditions during tests. In addition, the dark current–voltage (I–V) and the optical output power–current (L–I) characteristics of VCSEL test structures were measured at room-temperature after the tests. Especially, the optical output power of VCSEL was defined as the photocurrent of the calibrated photodiode (see Fig. 2b). The failure of the VCSELs is defined by the 3 dB-decrement in optical output power or the 50% change of the threshold current compared to the initial value, respectively [12,13].

4. Results and discussion

Prior to the accelerated life tests, the temperature dependence of the dark current, the threshold current and the photocurrent
on the VCSELs corresponding to maximum optical output power is presented in Figs. 3 and 4. The temperature dependence of dark current at the reverse-bias of 2 V is shown in Fig. 3. As shown in Fig. 3, the activation energy is calculated to be 0.434 eV. It can be resulted from the carrier generation either by the thermally induced excess carriers at the elevated temperature or by the excess tunneling carriers by the n⁺–p⁺ tunnel junction. Since the temperature dependence of dark current appears to be linear, the temperature range can be considered as a test condition for the accelerated life tests to estimate the long-term reliability of VCSEL [14]. In addition, the activation energy can be induced from the geometrical effect of the barrier lowering due to the field across each QW or the uncompensated positive charges remained inside during the electron emission from the well [15]. As the temperature increases up to 50 °C, the threshold current increase from 2 mA to about 4.6 mA and the maximum photocurrent decrease from 0.5 mA to 0.03 mA (see Fig. 4). As the temperature increases, both the cavity resonance and the laser gain shift to longer wavelengths owing to the refractive index and band-gap temperature dependence, respectively. However, the difference in speed

Fig. 2. Testing and measurement environments: (a) high-temperature stress test, and (b) L–I–V room-temperature measurement.

Fig. 3. Temperature dependence of the dark current for VCSEL.
between the cavity resonance and the laser gain shift leads to these characteristic variations of the laser performance [16].

In order to examine the characteristic variation of the test VCSELS at high-temperature, the high-temperature storage tests are performed at 200 °C and the results are shown in Fig. 5. The degradation of the VCSELS is not observed beyond 1000 h. For the benefit of time efficiency, the accelerated life tests for VCSELS are then performed with the extreme operating current of 11 mA at two different ambient temperatures of 200 °C and 250 °C. The results of the accelerated life tests for the VCSELS are summarized in Table 2. The median lifetime was measured to be 267.7 h at 200 °C and 41.8 h at 250 °C. Consequently, the each standard deviation for the lognormal distribution was calculated to be 0.24 h at 200 °C and 0.23 h at 250 °C.

The characteristic variations of the current–voltage (I–V), the optical output power–current (L–I) and threshold current versus time curve during the accelerated life tests at 200 °C and 250 °C are presented in Figs. 6–8, respectively. In the early stage of aging,
the threshold current is decreased and the output optical power is increased due to the enhancement of the contact resistance. Afterward, however, the threshold current is increased and the output optical power and the differential quantum efficiency are decreased indicating that the gradual degradation of the VCSEL test structures is activated.

![Fig. 7. Testing results of VCSEL characteristics for biased baking at 200 °C: (a) room-temperature L-I curves, and (b) threshold current.](image1)

![Fig. 8. Testing results of VCSEL characteristics for biased baking at 250 °C: (a) room-temperature L-I curves, and (b) threshold current.](image2)

Fig. 9. Lognormal projection of time-to-failure versus percent of cumulative failure for VCSELs after the life tests at 200 °C and 250 °C.

Fig. 10. Arrhenius plot of median device lifetime for VCSEL test structures as a function of reciprocal aging temperature.
The relationship between dark current and threshold current can be analyzed via mathematical threshold current model. General threshold current of laser diodes, $I_{th}$, is simply modeled using the recombination loss current ($I_R$), the vertical leakage current ($I_V$), and the lateral leakage current ($I_L$) by the following equation [17]:

$$I_{th} = I_R + I_V + I_L$$

Initially, stimulated emission comes to be vigorously with the high applied energy, such as the temperature and the electrical stress. Therefore, $I_R$ is decreased and the optical output power is increased for a short period of time. As the stress time goes by, however, degradation comes to be more prominent and finally leakage current ($I_V$ and $I_L$) are increased. Thus, $I_{th}$ is increased drastically in the failure VCSEL device. This can be confirmed via the $I$-$V$ characteristic variation shown in Fig. 6.

---

**Fig. 11.** Three degradation modes along the level of threshold current and dark current as a function of the aging time: (a) gradual mode, (b) catastrophic mode, and (c) rapid mode.
The percentage of the cumulative failures versus the lognormal projection of the device time-to-failure after the accelerated life tests is shown in Fig. 9. The percentage of cumulative failures behaves almost linearly with the lognormal projection of the device time-to-failure. These results imply that failures follow a lognormal distribution and that the failure mode is the wear-out type. Due to the limited number of samples, the reliability testing is performed at two temperatures. From the test results, the confidence intervals on the mean responses of the 200°C and 250°C tests are the ranges from 21.9 to 78.0 and from 25.0 to 75.0 in the cumulative failure plot, respectively. In addition, the slopes of the fitting line in the cumulative plot for the 200°C and 250°C tests are found to be 2.51 and 2.61, respectively, indicating that the data lies within the confidence interval with the 95% confidence level. From these results, it can be concluded that the degradation mechanisms of the 200°C and 250°C tests are statistically the same and the testing at two temperatures can be statistically sufficient to support the reliability of the data.

The Arrhenius plot of median device lifetime for the VCSEL test structures is exhibited in Fig. 10. From this plot, the activation energy of the device aging process is computed to be 0.79 eV. Using this activation energy level, the median lifetime can be estimated to be $2 \times 10^7$ h at room-temperature. Degradation behaviors of the VCSEL obey the lognormal distribution relatively well. So, the failure probability of the device as a function of time, $P(t)$, can be followed as:

$$P(t) = \frac{1}{\sigma \sqrt{2\pi}} \int_0^t \frac{1}{t} \exp \left[ -\frac{\left(\ln t - \mu\right)^2}{2\sigma^2} \right] dt$$

where $\mu$ is the average device lifetime and $\sigma$ is its standard deviation [11]. Along with the lognormal plot, this expression provides a quantitative method of evaluating the likelihood of failure for a VCSEL as a function of its age.

Using previous and additional aging tests results for the failure analysis, the failure modes could be categorized into three modes such as the gradual mode, the catastrophic mode, and the rapid mode along with the level of degradation of dark and threshold current according to the duration of reliability tests. Fig. 11 shows the threshold and dark current of each mode measured at room-temperature as a function of time before the failure of the device. Fig. 11a shows the gradual degradation that the device degradation

<table>
<thead>
<tr>
<th>Table 3</th>
<th>Summary of the classified indexes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification</td>
<td>Bias measured (V)</td>
</tr>
<tr>
<td>Index_p</td>
<td>–2</td>
</tr>
<tr>
<td>Index_f</td>
<td>–2</td>
</tr>
</tbody>
</table>

48 K.H. Rhew et al. / Microelectronics Reliability 49 (2009) 42–50
happens steadily over a long period of time. This degradation can be derived from a leakage path by formation of point defect clusters, which can gradually increase the dark current or decrease the optical output power [18]. The catastrophic degradation is shown in Fig. 11b. The notable distinction of the catastrophic degradation which is different from gradual degradation is the abrupt degradation after a certain point. Difference in these two degradation modes emerged from the variation of threshold current and dark current over an aging time in Fig. 11a and b. Fig. 11a represents that the device characteristics are degraded gradually according to the duration of an aging time and Fig. 11b displays that the device characteristics are almost constant up to the right before the device failure. This catastrophic failure is caused by unintentional current surges, gross damage to the mirror or certain defects by catastrophic optical damage (COD) [18]. Finally, the rapid degradation depicted in Fig. 11c features the rapid degradation of device at the beginning stage of the tests. This degradation is occurred by formation of non-radiative regions and initially contained defects [18].

For the VCSEL test structure in this work, the device failure can be affected by two possible electrical degradation mechanisms. One mechanism involves tunneling or dopant migration of the passivation layer resulted in an increase of reverse-bias leakage current, which eventually leads to the device failure. The other mechanism involves the overshoot of the excited carriers without emission in the active region and results in the degradation of the optical output power while exhibiting similar levels of reverse-bias leakage current before the test.

In order to determine the correlation between VCSEL failure and the device characteristics, the impact of the dark current and the optical output power on the VCSEL lifetime should be analyzed. The dispersions of the VCSEL lifetime by extracting duration taken for initial dark current to increase up to about 100 times at the bias voltage of $\frac{2}{\sqrt{C_0}}$ V are plotted in Fig. 12. The relationship between the extracted index for the dark current and the lifetime was observed in two ways. For the case of the index denoted by $'p'$, the dark current is extracted from measured data when the dark current increases up to 100 times of the initial value. For the case of the index denoted by $'f'$, the dark current is extracted from the extrapolation with increment of the dark current measured before failure. These indexes are summarized in the Table 3. As can be seen in Fig. 12, the VCSEL lifetime and the extracted indexes have a decently exponential dependency. It means that the $I-V$ characteristics are correlated with the device lifetime. The correlation between both indexes and the lifetime is reasonable since the reverse current of the VCSEL at the reverse voltage of $\frac{2}{\sqrt{C_0}}$ V is generally considered in the saturation region so that the variation of the dark current is rather stable. From the results, it can be found that the variation of the dark current at $\frac{2}{\sqrt{C_0}}$ V is suitable to estimate the reliability of the VCSELs. It can be also concluded that there is a relationship between the current–voltage characteristics ($I-V$) and the device lifetime. Although the reliability of VCSELs is generally estimated by the optical power, the dark current can be an alternative index to assess the degradation of the test VCSELs.
Based on the life test results, the correlation between the initial characteristics of the VCSELs, such as the dark current, and the VCSEL reliability is investigated. Due to the random variation of the VCSEL fabrication process, the dark current levels of VCSEL are critically varied. In order to analyze the correlation effect, the VCSELs used in this study are divided into two groups according to initial dark current level and the optical characteristics using additional experiments to obtain samples of each group for statistical analysis. The two groups can be determined by the different processing steps and the process variation of the wet etching. The two groups can be determined by the different processing steps and the process variation of the wet etching. The two groups can be determined by the different processing steps and the process variation of the wet etching.

The group A consists of the samples with initial dark current level with relatively lower $L-I$ characteristics and the group B consists of the samples with relatively lower initial dark current level compared to the group A with relatively lower $L-I$ characteristics (see Fig. 13). Initial characteristics and reliability testing results of the sample device in two groups with remarkable contrast in electrical and optical properties are exhibited in Figs. 14 and 15.

While the group A surprisingly exhibited the degradation of device in the rapid mode at the beginning of testing, the degradation mechanism of the group B was occurred either in the gradual or catastrophic mode. The mechanism of the rapid degradation in group A is considered as the infant mortality. Even though the initial $L-I$ characteristics are desirable (such as the low threshold current and the high optical output power), the VCSEL is demonstrated to be early failure which is not desirable for the long-term reliability. It is observed that though the VCSEL with high-level of dark current at initial stage shows the improvement of the optical characteristics, it can have an unfavorable effect on the long-term reliability.

5. Conclusion

Long-term reliability of all monolithic 1.55-$\mu$m etched-mesa VCSEL with tunnel junction of $n$–$p$–$i$–$n$ structure has been evaluated using the proposed high-temperature aging tests and the degradation of $I-V$ and $L-I$ characteristics has been observed. Based on the test results, a lognormal failure model was acquired from the failure time of respective elements at each testing environment. The activation energy for the VCSEL failure mechanism is calculated to be about 0.79 eV and the extrapolated median VCSEL lifetime at room-temperature is about $2 \times 10^7$ h. Therefore, it can be concluded that the all monolithic 1.55-$\mu$m etched-mesa VCSEL with tunnel junction has the sufficient long-term reliability for high-speed optical communication system applications.

Degradation mode was classified into three types along the level of degradation of threshold current according to duration of aging tests of the VCSEL and the failure mechanism on each degradation mode was analyzed. It was found that the dark current variation is closely correlated with the device lifetime and the dark current can be used as the reliability indicator of VCSELs. In addition, the high-level dark current at initial stage can significantly reduce the device lifetime despite of a favorable $L-I$ characteristic. Therefore, it can be concluded that the dark current, which is a process-related factor should be minimized in the fabrication process to ensure sufficient reliability for VCSELs.

References