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

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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-λ thick active region between two n-InP layers consists of seven strain compensated InAlGaAs quantum wells (QW). The structure consisting of a double intracavity contact with the 2.0-λ 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

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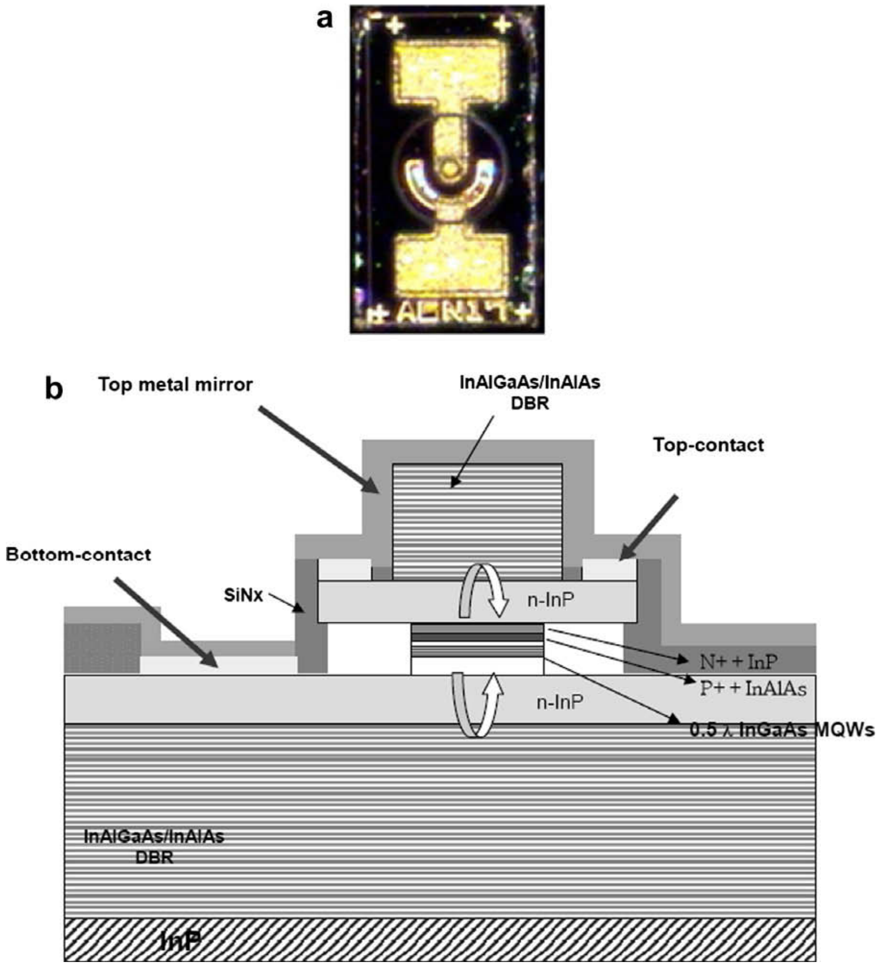

Fig. 1. (a) Microscopic image (200×), and (b) cross-sectional schematic for the test VCSEL structure.

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-λ 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.

Table 1
Summary of test conditions.

Test temperature (°C)	Operating current (mA)	# Of samples
200	11	7
250	11	8

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]:

$$R = R_0 \times \exp(-E_a/kT)$$

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