Long term reliability study and life time model of quantum cascade lasers

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Here, we present results of quantum cascade laser lifetime tests under various aging conditions including an accelerated life test. The total accumulated life time exceeds 1.5 million device hours. The longest single device aging time was 46.5 thousand hours without failure in the room temperature aging test. Four failures were found in a group of 19 devices subjected to the accelerated life test with a heat-sink temperature of 60 °C and a continuous-wave current of 1 A. Failure mode analyses revealed that thermally induced oxidation of InP in the semi-insulating layer is the cause of failure. An activation energy of 1.2 eV is derived from the dependence of the failure rate on laser core temperature. The mean time to failure of the quantum cascade lasers operating at a typical condition with the current density of 5 kA/cm² and heat-sink temperature of 25°C is expected to be 809 thousand hours.

After more than two decades of development [1-2], quantum cascade lasers (QCL) have become the most important and promising laser source in the mid/far infrared wavelength range, and they have gradually been introduced in various commercial applications, including trace gas sensing, explosive detection, infrared counter measures, *etc.* [3-5]. The expected life time of QCLs is a very important issue, especially for industry and end users. Although many life tests of QCLs under various aging conditions have been reported [6-10], no life time model has ever been reported. It is believed that QCLs rarely fail or barely degrade even after several thousand hours of aging, because of a low failure rate. This low failure rate makes it difficult to accumulate enough failure instances and to obtain a life time model. Here we report a QCL life time model based on the aging data from an accelerated life test study that lasted four and a half years.

We started a group of QCL life tests in 2010. A summary of 4 major aging tests is given in Table 1. Most of them were reported previously after several thousands of hours of aging test passed [6, 11-12]. Test 1 contains 9 Fabry-Perot (F-P) QCLs, which were mounted on Coppertungsten (CT) mounts and aged with a continuous-wave (CW) current of 0.85A at 20 °C. Test 2 is the accelerated life test. It contains 19 F-P QCLs (on CT mounts), which were aged with a CW current of 1 A at 60 °C. Test 3 contains 12 distributed-feedback (DFB) QCLs (on CT mounts), which were aged with a quasi-CW (QCW) current with 50% duty cycle of 0.37 A at 25 °C. The details of lasers structures, testing conditions, and preliminary results of test 1, 2, and 3, were reported in references [6], [11], and [12], respectively. Test 4 contains 12 uncoated F-P QCLs, which were mounted epi-down on silicon-carbide (SiC) submounts, which were further mounted on D-mounts, rectangular mounts made from copper-tungsten. Every QCL contains a core of 31 active stages, with a gain peak wavelength at 4.6 µm. The growth, fabrication, and characterization of these chips are similar to those reported in reference [11]. The 12 F-P QCLs were aged with a QCW (50% duty cycle, 166.7 Hz pulse rate) current of 1 A. The aging temperature was set at 60 °C initially, and was later changed to 45 °C so that we could combine

it with some other tests together in our life test system. All QCLs discussed here were processed as buried heterostructure (BH) lasers, and laser cores are buried about $4 \sim 5 \mu m$ deep beneath the metal layer. The fabrication processes of those lasers were identical (with the exception of grating definition for DFB wafers), but stripe widths of lasers within the tests vary by a few μm due to the variation in stripe widths on the mask used for fabrication. In each test, all lasers were connected in series, and a fixed current was used, therefore the variation of stripe width resulted in differences in output power from each device during the life test.

The in-situ power and voltage monitoring data as a function of aging time of test 1 are shown in Fig. 1. Judging from the voltage readings, we conclude that all 9 QCL chips survived CW aging with an aging time close to 47000 hours. In the power reading data, 3 devices showed signs of degradation. However, we took those devices out of the life test system and measured pulsed and CW light-current-voltage (LIV) characteristic curves with a calibrated power meter [6]. By comparing the LIV data before and after the life test, as shown in Fig. 2 (a), it was apparent that the devices had not degraded. The output power of these devices after aging remained the same or even become higher than those measured before aging. We believe that the power reading decreases in the life test system may came from either a degradation of thermal contact between the submounts and the heat-sink plate or a degradation of thermopile detectors used in the system.

The power and voltage data of QCLs in test 2 are shown in Fig. 3. In this test, 3 devices failed at 25000, 34000, and 38500 hours of aging, respectively, with sudden large voltage drops. In the power reading, an additional 8 devices showed signs of degradation. However, our LIV tests of the 8 devices showed that 7 out of the 8 devices had CW LI curves after aging similar to those before aging. One example is shown in Fig. 2 (b). Hence, these 7 devices are not

considered failures. We believe that the reason for the decrease in power readings is same as discussed above. Only one device, L2-17, showed a power drop of 70% (much higher than the 20% we consider as a failure criteria) and a threshold increase of 0.2A in a pulsed LIV. Thus, we consider this device to be a failure. Therefore, we count a total of 15 devices that passed the accelerated aging of 39000 hours.

In test 3, the power and voltage readings of the 12 DFB QCLs have not shown any significant drift from the latest reported data [12]. Therefore the plots power and voltage readings as function of aging time are not shown here.

The power and voltage readings of 12 F-P QCLs on SiC submounts are shown in Fig. 4. The temperature of the plate was changed from 60 °C to 45 °C at 8500 hours of aging. There are two sections (around 8800 and 10000 hours) where the voltage readings are lower than normal values because the current and temperature settings in the system were slightly different from desired values due to set point errors. 3 devices did not lase at either 60 °C or 45 °C plate temperatures, due to high threshold currents. The voltage readings of the 3 devices were normal, except one showed a noisy signal. This was most likely due to an imperfect electrical contact after the temperature was changed. Nevertheless, 12 devices passed 12600 hours of QCW aging, and no sign of degradation was found in this batch of devices.

With the 4 life tests, we accumulated aging data of 1.5 million device hours in total. In test 2, we observed 4 failures. Based on the variation of stripe widths of the 19 F-P QCLs, we summarized the information such as aging current density, and estimated the average core temperature, in Table 2. The thermal impedances were derived by combining measurements in DFB QCLs in [12] with the trend of thermal impedances vs. stripe width in [13]. We further

estimated the failure rate (FR) at 60% confidence, and at each configuration (stripe width) based on the formula [14]:

$$FR = \frac{10^9 N\gamma}{t_{tot}} , \quad (1)$$

where t_{tot} is the total device hours of aging, N is the number of failures, and γ is a factor that varies with N. If there is no failure, N is still treated as 1, but γ is 0.92. Otherwise, γ equals to 2.02, 1.55, or 1.39, if the number of failures is 1, 2, or 3, respectively. We plot FR as function of current density in Fig. 5 (a). If we assume that the failure is solely accelerated by current density, we can roughly estimate the exponential index n as 3.2 in the dependence expression: $FR \propto J^n$, based on the fitting curve, where J is the current density. We also plot FR as function of the core temperature in Fig. 5 (b). If the failure in the life test is solely thermally accelerated, we can roughly estimate a thermal activation energy E_a as 1.2 eV, with the expression $FR \propto \exp(-E_a/kT)$, where T is the core temperature. With a proper estimation of n or E_a , a mean time to failure (MTTF) of the QCL devices at certain working conditions can easily be predicted, as shown in Fig. 5 (c).

We also performed failure analysis for the 4 failed devices. Three devices exhibited catastrophic failure, namely a sudden large drop of voltage. Inspections of those devices show similar signature, in which the facet exploded at the core area, the same as reported in reference [15]. The 4th failed QCL, L2-17, which had a significant power decrease, was found to have an intact facet. However, an unknown belt shape dark substance was observed on the front facet, as shown in Fig. 6 (a). It seems that the dark substance partially covers the laser core area and results in a degradation in output power. The dark substance was also observed on facets of many other QCLs from test 2, including the devices that failed catastrophically. The position and

shape of the dark substance coincide with those of the semi-insulating (SI) InP layers. Unlike that on device L2-17, the substance on other survived devices did not cover the laser core area, and the performance of those devices was not impacted. For the devices that failed catastrophically, we attribute the failures to additional stress resulting from a higher temperature increase at the laser facets due to absorption of the optical power by the dark substance near the laser core.

Scanning Electron Microscope (SEM) with Energy-Dispersive X-ray spectroscopy (EDX) analysis showed that the dark substance did not contain elemental carbon and is not organic contamination but instead contained oxygen, as shown in the inset of Fig. 6 (a). To identify this material, we did further study with Transmission Electron Microscopy (TEM). A TEM sample was extracted from the area near the laser core using focused ion beam (FIB) techniques, as indicated by the rectangle in Fig. 6 (a). The TEM image in Fig. 6 (b) clearly reveals a sponge-like bump that grows out of the InP, instead of some foreign material attached or stuck to the facet since the original straight facet interface is replaced by a curved interface between the bump and InP. EDX mapping confirmed that the substance consists of In, P, and O, as shown in Figs. 6 (c), (d), and (e). This data indicates that the InP was oxidized during the open heat sink life test. High resolution imaging, electron diffraction, and Electron Energy Loss Spectroscopy (EELS) reveal that the oxidized layer consists of a nanoscale mixture of In₂O₃ and P_2O_5 . In the high resolution image, Fig. 6 (f), small crystalline and amorphous domains are observed. The crystalline domains produce a ring pattern in electron diffraction (inset of Fig. 6 (f)) that can be indexed according to In_2O_3 . EELS spectrum from the oxide, shown in Fig. 6 (g), show that the P L₂₃ peak shifts about 9 meV, as compared to that in the InP substrate, indicating

a change from P^{-3} to P^{+5} This suggests the amorphous domains are P_2O_5 consistent with oxidation studies of InP reported previously [16-17].

Although we don't know exactly why the oxidization would start near the SI InP, we suspect that the iron in the SI layer somehow helped or initiated this process. On the other hand, the oxidation behavior is not found in any other device in the other 3 tests, which have lower test temperatures. This suggests that a high temperature is essential for the oxidation process. With this finding we believe that the failures observed in test 2 are thermally induced.

In summary, we have performed a study of four QCL life tests, including both F-P and DFB QCLs, with various aging conditions, and we have accumulated a total life time of 1.5 million device hours. The longest running device reached more than 46 thousand hours, which is equivalent to 5.3 years of non-stop operation. We experienced few device failures and little degradation, except in the accelerated life test, in which devices were stressed at 60 °C. Four failures were observed out of 19 devices in that test. Based on the distribution of failures with respect to core width and estimated core temperature, we estimated a thermal activation energy of 1.2 eV and a current density exponent of 3.2, at 60% confidence. Failure mode studies with SEM, TEM, EDX, and EELS analyses determined that thermally promoted oxidation of InP on uncoated facets under high temperature condition is the major failure cause of QCLs in the accelerated life test. We conclude that QCLs are intrinsically very reliable semiconductor lasers. The MTTF of QCLs operating at a typical condition with a CW current density of 5 kA/cm² and a heat-sink temperature of 25 °C is about 809 thousand hours or 92 years. Although there is a potential failure mechanism with a low failure rate due to the thermal excited oxidation of InP material in QCLs, it can be mitigated by avoiding high temperature operation, or implementing proper device packaging, coating or housing methods.

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¹ J. Faist, F. Capasso, D. L. Sivco, C. Sirtori, A. L. Hutchinson, and A. Y. Cho, *Science* **264**, 553 (1994).

² Y. Yao, A. Hoffman, and C. Gmachl, *Nature Photonics* 6, 432 (2012).

³ R. F. Curl, F. Capasso, C. Gmachl, A. A. Kosterev, B. McManus, R. Lewicki, M. Pusharsky, G. Wysocki, F. K. Tittel, *Chem. Phys. Lett.*, **487**, 1 (2010).

⁴ F. Fuchs, S. Hugger, M. Kinzer, R. Aidam, W. Bronner, R. Lösch, Q. Yang, K. Degreif, F, Schnürer, *Opt. Eng.* **49**, 111127 (2010).

⁵ M. Razeghi, *Proc. SPIE* **8543** Technologies for Optical Countermeasures IX, 854304, Edinburgh, United Kingdom, September 24, 2012.

⁶ F. Xie, C.G. Caneau, H. LeBlanc, C. Page, S. Chaparala, O. Deichmann, C. Hughes, and C. Zah, *Opt. Eng.*, **49**, 111104 (2010).

⁷ C. Pflügl, W. Schrenk, S. Anders, G. Strasser, C. Becker, C. Sirtori, Y. Bonetti, and A. Muller, *Appl. Phys. Lett.* **83**, 4698 (2003).

⁸ L. Diehl, D. Bour, S. Corzine, J. Zhu, G. Höfler, M. Loncar, M. Troccoli, and F. Capasso, *Appl. Phys. Lett.* **88**, 201115 (2006).

⁹ A. Evans and M. Razeghi, Appl. Phys. Lett. 88, 261106 (2006).

¹⁰ A. Tsekoun, R. Go, M. Pushkarsky, M.Razeghi, and C. K. N. Patel, *Proc. Natl. Acad. Scl. USA* **103**, 4831 (2006).

¹¹ F. Xie, C. Caneau, H. LeBlanc, N. Visovsky, S. Chaparala, O. Deichmann, L. Hughes, C. Zah, D. Caffey, and T. Day. IEEE *J. Selected Topics in Quant. Elect.* **17**, 1445 (2011).

¹² F. Xie, C. Caneau, H. P. Leblanc, N. J. Visovsky, S. Coleman, L. C. Hughes, and C. Zah, IEEE *J. Selected Topics in Quant. Elect.* **18**, 1605 (2012).

¹³ S. C. Chaparala, F. Xie, C. Caneau, C. Zah, and L. C. Hughes, IEEE *Transactions on Components, Packaging and Manufacturing Technology*, **1**, 1975, (2011).

¹⁴ G. Yang, G. Smith, M. K. Davis, D. Loeber, M. Hu, C. Zah, and R. Bhat, IEEE *Photonics Tech. Lett.*, **16**, 2403, (2004).

¹⁵ Q. Zhang, F. Liu, W. Zhang, Q. Lu, L. Wang, L. Li and Z. Wang, *Appl. Phys. Lett.* **96**, 141117 (2010).

¹⁷ J. Gao, Q. Zhao, Y. Sun, G. Li, J. Zhang, and D. Yu, *Nanoscale Res. Lett.* 6, 45 (2010).

Test	Sample	Sample details	Current	Heat-sink	Time	Number
	size			temperature	(hrs)	of failure
1	9	CT, F-P,	0.85 A CW	20 °C	46.5 k	0
		Ga _{0.33} InAs/Al _{0.65} InAs, 2×10 ¹⁶				
2	19	CT, F-P,	1 A CW	60 °C	39.3 k	4
		Ga _{0.33} InAs/Al _{0.65} InAs, 2×10 ¹⁶				
3	12	CT, AR, DFB, Ga _{0.357}	0.37 A QCW	25 °C	11.4 k	0
		InAs/Al _{0.654} InAs, 3×10 ¹⁶				
4	12	SiC/WCu, , F-P, Ga _{0.33} InAs /	1 A QCW	60/45 °C	12.6 k	0
		Al _{0.65} InAs, 2.5×10 ¹⁶				

Table 1. The summary of 4 QCL life test studies with various configurations. The sample details include type of mount, type of coating (if coated), type of devices (F-P or DFB), material composition in cores, and the averaged doping density (in the unit of cm⁻³) in laser cores.

Stripe width (μm)	Sample size	Current density (kA/cm²)	Average core temperature (K)	Device · hours	Failures	Failure Rate (kFIT)
6	8	3.70	399	312000	0	2.949
5.5	4	4.04	403	141700	1	14.255
5	2	4.44	406	77600	1	26.031
4.5	2	4.94	410	78000	0	11.795
3.5	3	6.35	420	98700	2	31.408

Table 2. The summary of stripe widths, size of sample, current densities, total device hours,

number of failures, and failure rate of each configuration in test 2.

¹⁶ X. Liu, M. S. Denker, and E. A. Irene, J. Electrochem. Soc., 139, 799 (1992).



Fig. 1. (a) The voltage readings of 9 QCLs as function of time in life test 1. (b) The optical power in-situ reading of 7 QCLs as function of time in life test 1. Two lasers did not lase at given CW aging current.



Fig. 2. Pulsed and CW LIV before and after aging of device (a) L1-3, and (b) L2-18. The power of the pulsed LIV is peak power which was calculated by dividing the average power by the pulsed duty cycle.



Fig. 3. (a) The voltage readings of 19 QCLs as function of time in life test 2. (b) The in-situ optical power reading of 19 QCLs as function of time in life test 2.



Fig. 4. (a) The voltage readings of 12 QCLs as function of time in life test 4. (b) The insitu optical power reading of 12 QCLs as function of time in life test 4. 3 lasers did not lase at given QCW aging current.



Fig. 5. (a) The failure rate as a function of current density. The dash line is a linear fitting curve, and the slope is 3.2. (b) The failure rate as a function of averaged temperature of laser core. The dash line is a linear fitting curve, and the slope yields an activation energy of 1.2 eV. (c) Projected mean time to failures (MTTF) is plotted in both thermally and current density accelerated failure models. In the former, MTTF is plotted as functions of operating temperatures or operating current densities, with a fixed current density of 5 kA/cm² or a fixed temperature of

30 °C, respectively. In the latter, MTTF is plot as a function of operating current densities, with n=3.2 and an operating temperature of 60 °C, same as the condition of test 2.



Fig. 6 (a) The front facet image of laser L2-17, showing a dark belt shape substance appearing near the bottom of facet, matching the position of semi-insulating layer. The inset shows an EDX map of oxygen at the corresponding position. The red rectangle shows the position where a TEM sample was extracted. (b) TEM image of the sample showing the InP substrate and the belt-shape of unknown substance found on laser facet. EDX maps for (c) In, (d) P, and (e) O show the interfacial material is an oxide. (f) High resolution image showing the oxide region at the

interface consists of a nanoscale mixture of crystalline and amorphous regions. Electron diffraction (inset) shows the crystalline phase is In_2O_3 as indexed. (g) EELS data of P L₂₃ edge at the points marked X and Y in (b) indicate a change from P⁻³ in the InP substrate to P⁺⁵ in the oxide, suggesting the amorphous domains are P₂O₅.