VCSEL reliability in ATLAS and development of robust arrays

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ABSTRACT: Vertical Cavity Surface Emitting Lasers (VCSELs) are used for the readout and control of all ATLAS detectors at the LHC. Reliable VCSELs have been developed by using extensive Failure Analysis (FA) techniques to eliminate or reduce the rates of random failures. Some of these FA techniques are described with illustrations from failed VCSEL channels from ATLAS operation. However VCSELs are very sensitive to several environmental factors. The reliability of the VCSELs in the different systems has been varied. In addition to FA, controlled experiments have also been very useful in determining the cause of failures. The programmes to mitigate these failures for the two systems most affected are reviewed. A summary of VCSEL reliability and the outlook for ATLAS operation is given.

KEYWORDS: Optical detector readout concepts, Large detector-systems performance.

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1. Introduction

VCSELs are used for optical transmission for all ATLAS detectors[1]. There have been various problems with the reliability of the VCSELs used in some but not all of the sub-systems. This paper briefly reviews the design of VCSELs and the potential reliability issues. Some of the techniques used in Failure Analysis (FA) are explained with examples from studies of devices that failed during ATLAS operation. Estimates of the failure rates from the different systems are given. The attempts to diagnose the causes of the problems are described. The mitigation strategies for the two sub-systems most seriously affected are described. Finally some conclusions about VCSEL reliability and the outlook for ATLAS operation will be given.

2. Advantages and Disadvantages of VCSELs

VCSELs are widely used in multimode optical links for distances up to about 1 km. The main advantages of VCSELs over Edge Emitting Lasers (EELs) are cost (because they can be tested at the wafer level) and low power consumption because of the low laser threshold and high slope efficiency. As VCSELs are made from GaAs substrates they potentially suffer from the growth of Dark Line Defects (DLDs)[2]. The very high minority carrier concentrations in semiconductor lasers allows any defects to grow. These defects act as centres for non-radiative transitions so that any defects in the active volume of the device will increase the laser threshold. These defects in the Distributed Bragg Reflector (DBR) mirror tend to grow slowly towards the active region but once they reach the active region they grow rapidly resulting in a

rapid failure of the device. Reliable VCSELs therefore require very high quality starting material and extreme care over all environmental factors which can degrade the device.

3. Failure Analysis

In order to fabricate reliable VCSELs it is essential that causes of infant mortalities and random failures can be understood and be eliminated or reduced to an acceptable level. After random failures have been reduced to an acceptable level, accelerated aging tests are performed to validate the reliability of the VCSELs for many years of operation at standard operating conditions. A wide range of powerful diagnostic techniques are available and this paper gives a brief review of some of the methods that were used by ATLAS.

3.1 IV Analysis

The simplest diagnostic test that can be performed is a measurement of the current versus voltage (IV) of the VCSEL. Forward IV curves for working channels are very uniform and damaged channels show a characteristic shift. However this shift gives no indication as to the cause of the damage. Reverse IV curves are very sensitive to Electro Static Discharge (ESD) in that they show greatly enhanced reverse leakage below the breakdown threshold. Therefore this can be used as a powerful QA for very low level ESD but it cannot be used to prove unambiguously that ESD was the cause of the damage.

3.2 Electroluminescence

Electroluminescence (EL) involves imaging the VCSEL when it is operated below laser threshold. A working channel should show a very uniform bright area, whereas damaged channels show significant dark areas where the minority carrier lifetime is reduced by the non-radiative recombination from the trap sites. An example of EL for a dead VCSEL from the LAr detector[3] is shown in Figure 1(a).

3.3 Electron Beam Induced Current

Another technique which can resolve active areas that have been damaged is Electron Beam Induced Current (EBIC). In this technique the induced electron current is measured as the primary electron beam is scanned in a Scanning Electron Microscope (SEM). The resulting current is sensitive to trap sites, hence defects show up as dark areas. EBIC is not normally used for VCSELs because of scattering from metal contacts. However it has been used successfully by ATLAS. An example EBIC picture¹ from a dead channel from a VCSEL array² (used in the pixel Timing, Trigger and Control (TTC) system[4]) is shown in Figure 1(b). As for all the first generation VCSEL arrays, these devices were designed for operation in dry environments and are expected to be sensitive to humidity during operation[5] (see section 4.2 for further discussion of the effects of humidity during operation).

¹ EL, EBIC and STEM Analysis performed by Evans Analytical Group, <http://www.eaglabs.com/>.

² Truelight TS-8B12-00, www.truelight.com.tw

Figure 1 (a) Electroluminescence image of a dead LAr OTx VCSEL channel and (b) EBIC image of a dead channel from a Truelight array.

3.4 Scanning Electron Microscopy

The most detailed information on the exact location of the damage comes from Scanning Electron Microscopy (SEM). In plan view SEM, only surface or shallow damage can be studied. If the location of the damage can be determined from EL or EBIC a very thin cut can be made using a Focused Ion Beam (FIB) and the sample analysed using Scanning Transmission Electron Microscopy (STEM). This technique was applied to the channel analysed by EBIC (Figure 1(b)). Defects can be seen clearly in the different layers of the device as illustrated by the Scanning Transmission Electron Microscope (STEM) picture² in Figure 2. The alternating layers of the DBR mirrors and the oxide implant can be seen clearly. Defects appear to spread out from the tip of the oxide and propagate to the active Multi-Quantum Well (MQW) layer. No structure is visible in the MQW because of the extensive damage.

Figure 2 STEM picture of a cross section of a dead VCSEL channel after the FIB preparation of the dead channel illustrated in Figure 1(b).

3.5 Optical Spectrum Analysis

Optical Spectrum Analysis (OSA) is a powerful, non-destructive technique for determining early signs of damage in working VCSELs. VCSELs are single longitudinal mode devices but have multiple transverse modes. While most of the optical power is contained in a few modes, the loss of the much lower power higher order modes is a strong indication for low-level damage[5].

4. VCSEL Reliability in ATLAS

Failure rates have been estimated for 11 different sub-systems in ATLAS. Some systems with a significant number of links have been operating for over 3 years with no failures. Other systems have seen a low rate of random failures. In the case of the VCSELs used for the readout of the Resistive Plate Chambers (RPC)[6], this was traced by the manufacturer to insufficient ESD control during wafer processing. The rate of failures in the LAr links is of particular concern as access to the devices requires a long process for opening of the End Caps. The most serious reliability problem was seen in the off-detector VCSELs used for TTC distribution for the SCT and Pixels. In this case the failures were accelerating with time and were therefore end of life failures rather than random failures.

4.1 Liquid Argon Calorimeter

The FA techniques used for the failed VCSELs from the Liquid Argon Calorimeter (LAr) showed very clear evidence of damage to the VCSELs but were unable to determine the cause.

An alternative approach to determining the failure was also used in which some damage to the device was deliberately introduced to see if it would lead to device failure. The most common cause of field failures in VCSELs is Electro Static discharge (ESD). Low level ESD pulses were applied and significant degradation was found using OSA after pulses of 300V were applied. VCSELs are known to be sensitive to humidity so another test was to intentionally expose a device to humidity. A hole was made deliberately in the TO can and the VCSEL was then run continuously in a normal lab environment with a relative humidity RH~50%. A clear decrease in the spectral width with time was seen.

The VCSELs in the TO can are normally hermetic but there is a possibility that damage to some devices left them non-hermetic. As with the other FA techniques, these tests only indicate possible causes of damage but can not unambiguously determine the cause of damage. In addition to these tests OSA was used for all channels and a clear population of suspect channels with narrow spectra was observed as shown in Figure 3.

Figure 3 Spectral widths versus serial number for the ATLAS Liquid Argon Calorimeter VCSELs. The black squares refer to devices which failed after the OSA measurements. The orange squares refer to devices whose spectra were classified as narrow according to a slightly different definition of the spectral width.

4.2 SCT and Pixel TX VCSELs

The TTC distribution for the SCT and Pixel detectors is based on 12 way VCSEL arrays [4]. The Mean Time To Failure (MTTF) was less than 1 year. ESD was suspected as the primary cause because this is the most common cause of VCSEL field failures. It is also known that low level ESD pulses can cause delayed VCSEL deaths and we performed tests that confirmed that this was possible for the Truelight VCSEL arrays. The ESD precautions used in the assembly of

the packages were reviewed and problems were identified. The ESD precautions were greatly improved and a complete production of new packages was performed. This resulted in a slight improvement but the devices still showed end of life failures with a MTTF ~ 1 year.

Another common cause of oxide implant VCSEL failures is exposure to humidity[7] during device operation. Single channel VCSELs are usually packaged in hermetic TO cans, whereas arrays are usually exposed to the environment. High pressure steam is used to grow the oxide implant. Holes are deliberately introduced to allow this growth[8], therefore humidity in the environment can easily reach the oxide. This is of concern when the device is biased, because an electrolytic reaction can deplete the Ga in the GaAs and this can act as a source of point defects which can subsequently grow. Different crates in the SCT had higher Relative Humidity (RH) than other crates and an inverse correlation between RH and MTTF was observed. Subsequent accelerated aging tests at different elevated temperatures and RH were performed and the results are summarised in Table 1. These showed that for elevated values of temperature and RH the MTTF was as low as a few hundred hours.

Table 1 Summary of VCSEL array accelerated ageing tests.

Test	T(°C)	RH(%)	Conditions	Results
1(a)	85	85	With epoxy	87% dead after 1000 hours
1(b)	85	85	w/o epoxy	100% dead after 1000 hours
2	60	85	With epoxy	85% dead after 2200 hours
3(a)	85	0	w/o epoxy	0 deaths after 1650 hours
3(b)	85	0	Pre-soaked 1 hr + pre-bias 50 hours + pre-baked 150 hrs.	0 deaths after 1950 hours
4	85	29	w/o epoxy	0 deaths after 1450 hours

The tests also showed that epoxy does not produce a humidity tight seal. Elevated temperature testing in very low RH showed no failures, providing further indications that humidity was the cause of failure. In order to perform a more direct controlled test, samples of Truelight VCSEL arrays were operated at 10 mA drive current at 50% duty cycle in both normal lab air (RH in the range from 40% to 60%) and dry N₂. OSA measurements were taken to monitor any changes in the spectral widths. The results for the VCSELs operated in dry N₂ showed no significant changes in the spectral width, whereas there was a clear narrowing of the spectra for the devices operated in normal lab conditions (Figure 4).

Figure 4 Spectral widths for VCSELs operated in air and dry N₂.

5. Mitigation Techniques

5.1 Liquid Argon Calorimeter VCSELs

For the LAr VCSELs the suspect channels with narrow spectra were replaced during the 2010/11 shutdown. Since then there have been no further failures. However a backup option with full optical redundancy has been developed in case there are further failures.

5.2 SCT and Pixel TX

These VCSEL are exposed to a normal humidity lab environment and the particular VCSELs used were not engineered to be robust in such an environment. It is very difficult to make completely hermetic packages for array VCSELs. However it is possible to manufacture moisture resistant VCSELs. Although the precise details are proprietary, the critical feature is to cover the holes in the Distributed Bragg Reflector (DBR) mirror used to allow steam to enter the device to grow the oxide implant. This can be done with a dielectric layer. Several companies have produced VCSELs which have passed damp heat tests and therefore would be expected to survive 10 years operation in normal lab humidity (see for example ref. [8]). Two different options are being pursued as well as the use of a compressor to provide low humidity (RH ~ 15%) air for the racks containing the VCSELs.

AOC arrays³ are being packaged in an identical way to the Truelight arrays. We have performed damp heat tests (85°C/85% RH) on a sample of 31 channels and have seen no failures in 3200 hours of operation at a DC current of 8 mA. We have also performed accelerated aging tests on 60 channels for which we monitored the spectral width. We saw no significant changes in 2000 hours operation at 70°C/85% RH.

ULM VCSEL arrays⁴ are being assembled in the iFlame package⁵. This uses VCSELs which are also qualified for operation in damp heat. This option has additional advantages in that it is a semi-hermetic package which will give it some additional protection against humidity ingress. Other attractive features are that the design is based on a minimal modification to a commercial 4 channel transceiver and that it uses flip chip bonding for the VCSEL which is a gentler process than wire bonding which can damage the chip. A modified version of the PCB which holds the BPM-12 laser driver chip[4] has been designed and built which is compatible with the iFlame package. Full functionality has been demonstrated with a 4 channel prototype. The next tests will involve reliability testing of the 12 channel iFlames. In order to increase the yield we are also investigating the use of higher power VCSEL arrays from ViS⁶.

6. Summary

Some ATLAS systems have seen no VCSEL failures after operation of more than 1000 channels for over 3 years, which is consistent with the manufacturer's claims for very high VCSEL reliability. Other systems have seen a low rate of random failures, which in one case was traced to ESD during wafer manufacture. Finally, one system has shown large, systematic failures. Many FA techniques are available and in some but not all cases these can uniquely identify the cause of failure. In general the high reliability of VCSELs can easily be compromised by damage from a range of environmental factors and extensive reliability testing of the final packaged product is essential.

In the case of the LAr OTx VCSELs, both ESD and humidity were identified as plausible damage mechanisms. OSA was demonstrated to be a very powerful diagnostic technique and has been used to screen out suspect devices. VCSEL arrays were found to be very sensitive to humidity. The SCT/Pixel TX VCSELs are being replaced with two solution using arrays designed for operation in high humidity environments. As an additional safety measure, the humidity in the racks is being reduced.

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