High Statistics Testing of Radiation Hardness and Reliability of Lasers and Photodiodes for the CMS Optical Links

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Abstract

A series of high statistics advance validation tests of lasers and photodiodes have been carried out to validate wafers intended for final production of optical transmitters and receivers for use in CMS optical links. A large data set has been collected which allowed a unique opportunity to characterise radiation damage and wearout in lasers and photodiodes with high statistics.

I. INTRODUCTION

The production of 60000 laser transmitters and 3600 photodiode receivers for optical link systems [1] for the readout and control of CMS Tracker, ECAL, Preshower and Pixels will soon be completed. Before each lot of devices was made, samples were taken from each starting laser and photodiode wafer and tested for radiation damage and long-term wearout rate in a series of advance validation tests (AVTs). In this paper we present a final summary of the results of these tests. This work represents the successful outcome of the test programme described in LECC 2001 [2], that followed 5 years of link development and prototype validation.

Radiation hardness and reliability are important areas of concern since the lasers and photodiodes are the optical link components most susceptible to radiation damage and wearout. These parts are also potentially inaccessible inside the CMS detector, in particular in the Tracker and Pixel systems, where the particle fluxes and doses are up to 2×10^{14}particles/cm^2 and 100kGy over the first 10 years of LHC running.

The laser die are Mitsubishi ML7CP8 1310nm multi-quantum-well InGaAsP/InP edge-emitters. The lasers are supplied to CMS by STMicroelectronics (STM) in a semi-custom package [1], which consists of the laser die attached to a silicon optical sub-mount and fibre-pigtail, with the submount having a simple lid-cover, rather than being housed in the standard STM mini-DIL package. The lasers were burned in at STM. The fibre pigtail and connectors were supplied by CERN having been pre-qualified fibre for radiation hardness and reliability.

The photodiodes are Fermionics InGaAs/InP FD80S8F photodiodes, with 80µm active diameter, mounted in a compact package. Some minor modifications were made to the standard Fermionics COTS part. As with the lasers, the fibre pigtail and connectors were pre-qualified parts supplied by CERN.

Since both the lasers and photodiodes are based on commercial off-the-shelf (COTS) components, their radiation hardness was not guaranteed. The goal of the AVT was therefore to confirm the suitability of the devices for use inside CMS, at the level of the laser or photodiode wafer before starting assembly of a large number of parts from that wafer.

II. AVT PROCEDURE

The AVT procedure is an integral part of a much wider quality assurance (QA) programme for the optical links project[3]. Only a brief summary is given here and full details of the AVTs on lasers and photodiodes are given in Refs [4] and [5]. The overall procedure is illustrated in Fig. 1 and each of the sub-procedures were defined based on methods that have been used successfully during the earlier prototype validation and subsequent qualification tests [6,7].

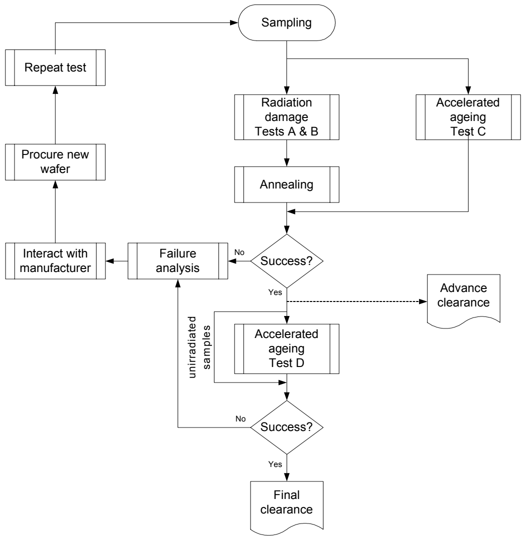

Figure 1: Flow chart of the laser AVT procedure. Conditions for tests A-D are given in Refs [4] and [5].

From each starting wafer, 30 samples were taken at random for the AVT. The parts were supplied in their specified final packaged form. 390 lasers in total from 60000 chips from 13 wafers have been validated in five laser-AVTs. 90 photodiodes from (at least) 3600 photodiodes from 3 wafers were tested in the photodiode-AVT. Steps A and B are measurements of damage and annealing with gamma and then neutron sources respectively (20 devices). Steps C and D involve accelerated aging (all 30 devices).

The gamma irradiation was made using a Co-60 source, with a total dose of 100kGy normally achieved over several days. The neutron irradiation used ~20MeV neutrons at CRC, Louvain-la-Neuve [8], with irradiation to at least $5\times10^{14}/cm^2$, over 6-8 hours. These levels of dose and fluence reflect the worst-case exposure inside the CMS Tracker [9]. The relatively high neutron fluence is equivalent to 2×10^{14}pions/cm^2 (with energies around 200MeV [7]), since the pions are significantly more damaging. The irradiations were made at room temperature with the devices normally under electrical bias. In addition to the radiation damage tests, the remaining 10 unirradiated samples, plus the 20 samples that were irradiated, were also subjected to accelerated ageing in an oven at 80°C for 1000hours, again under electrical bias, in order to measure the wearout rate.

Finally, there were some fixed acceptance criteria for the AVTs that 95% of the devices under test had to pass in order for the given wafer to be accepted. For the lasers, the combined effects of radiation damage (and annealing) and ageing were not allowed to increase the threshold current beyond the maximum dc current supply of the LLD [10] laser driver ASIC, which is 45mA (in the worst case). In addition the output efficiency of the laser must remain greater than 50% of the initial value. For the photodiodes, the irradiated photodiodes must have a dark current of less than 500μA at 5V reverse bias after 100kGy gamma dose and $5\times10^{14}n/cm^2$ (20MeV) neutron fluence. The photodiode responsivity should be no less than 0.4A/W at –5V for the same dose and fluence.

III. LASER RESULTS

The laser threshold currents were around 5mA at 20°C and the output efficiencies (out of the fibre) are ~40μW/mA (±20%) as specified for the application.

A. Radiation damage (AVT steps A and B)

There was no significant damage due to gamma irradiation to 100kGy in any of the AVTs, as well as during earlier measurements during qualification. Figure 2 shows an example of the threshold currents measured in a group of 60 lasers from 3 wafers (in AVT 3) before and after 100kGy.

Fig. 3 shows how the threshold and efficiency (normalised to the initial efficiency) changed during neutron irradiation in a group of 20 lasers from one wafer. The radiation damage in terms of either threshold current increase, or efficiency loss, was proportional to the neutron fluence.

A comparison of radiation damage in devices within a given wafer and between different wafers is made in Fig. 4. The data was first normalized to represent the damage expected after a fluence of $5\times10^{14}n/cm^2$ in 6 hours of irradiation at CRC, using the data taken for each laser during the first 6 hours of irradiation. The threshold increase in all the lasers was in the range of 20-30mA. The efficiency loss was between 20% and 30%.

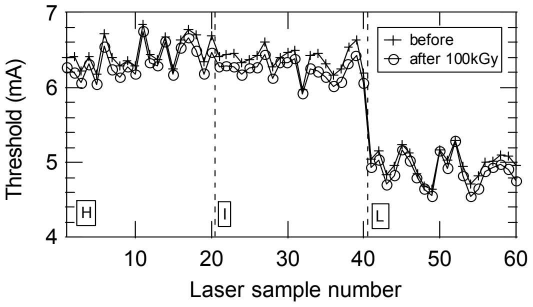

Figure 2: Threshold currents in sixty lasers from 3 wafers before and after 100kGy gamma irradiation.

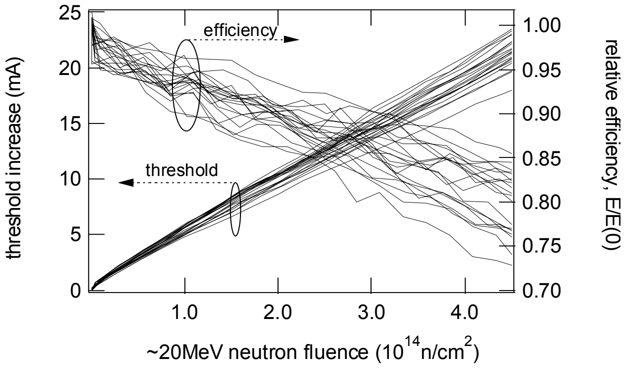

Figure 3: Threshold current change and normalized efficiency change in 20 lasers from one wafer irradiated with neutrons.

The annealing of the damage after neutron irradiation is illustrated in Fig. 5 for both the threshold current and efficiency in the irradiated lasers from one wafer. The data is also very similar for the other wafers. The annealing was observed to be proportional to log(anneal-time), from a point starting a few hours after irradiation for both threshold and efficiency damage. Both the threshold and efficiency damage anneal at the same rate, which confirms that these radiation damage effects are caused by the same set of defects.

The overall amount of annealing is very significant, especially in the context of the amount of annealing that might be expected to occur over the 10-year lifetime of the lasers inside CMS. The annealing observed in the AVTs is very similar to that measured during qualification of these lasers [7], when it was demonstrated, using thermal acceleration, that the same trend of annealing continues at least until 70% of the damage has recovered. The conclusion was that because of the continuous annealing of the damage over the lifetime of CMS the worst radiation damage expected is 5mA threshold increase and 5% efficiency loss.

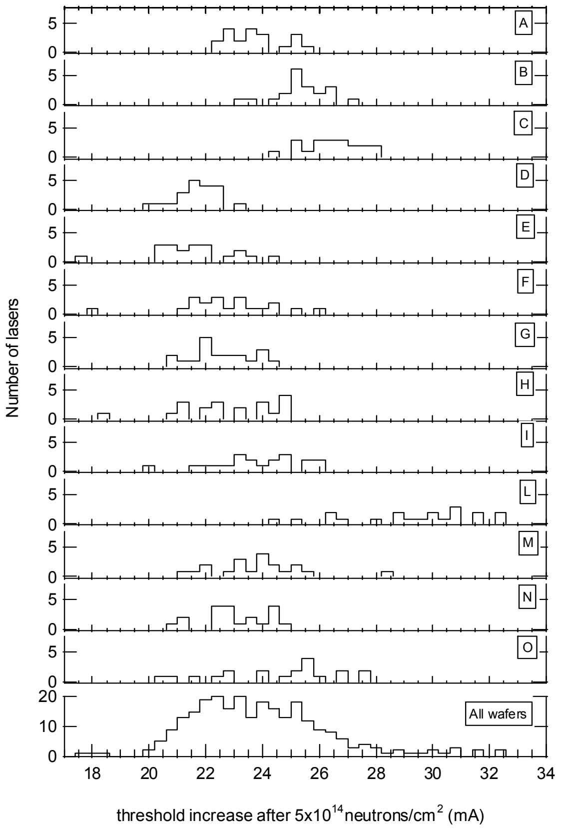

Figure 4: Comparison of the radiation damage across all 13 wafers tested, during AVTs 1-5 in terms of threshold damage.

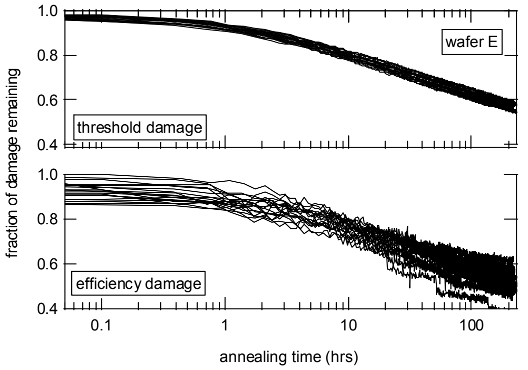

Figure 5: Annealing of the threshold current and efficiency damage after neutron irradiation for 20 lasers from one of the wafers.

B. Wearout during accelerated ageing (AVT steps C and D)

Fig. 6 shows an example of ageing data (60mA, 80°C) for unirradiated lasers. The measurements plotted were made periodically at 20°C to assess the wearout with respect to the initial properties of the device. Wafers N and O are similar to most of the other wafers that have been studies, in that they show little wearout in terms of increased leakage current or decrease in efficiciency. In contrast there is a clear increase in threshold current and loss of efficiency in devices from wafer M. This was similar to one other that was tested, wafer A.

The degradation appeared to be linear with ageing time and the time-to-failure (TTF) was estimated for each laser by extrapolating the ageing data to the failure criteria outlined earlier in Fig. 2, these were ΔI_{thr} = 55mA (current measured at 20°C) and ΔE=50% (at 20°C). A summary of the statistics for failure modes of threshold current increase and efficiency loss is shown in Fig. 6 for all the wafers. Although all the wafers passed this part of the AVT as expected, we had some reservations regarding the use of wafers A and M for CMS. As a consequence, lasers from wafer A have mainly been used for preproduction systems in CMS, and we are in discussion with the manufacturers to find a replacement for wafer M.

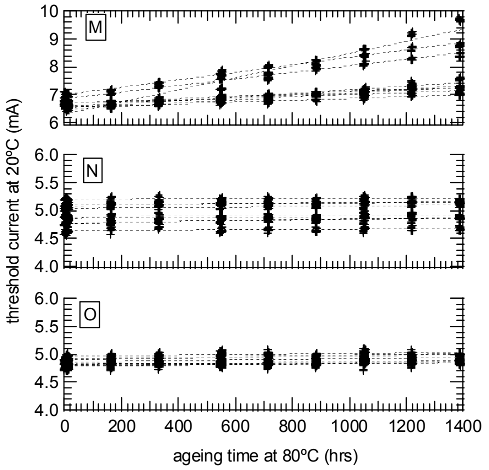

Figure 6: Threshold current degradation in unirradiated lasers from 3 wafers (M, N and O) during aging at 80°C.

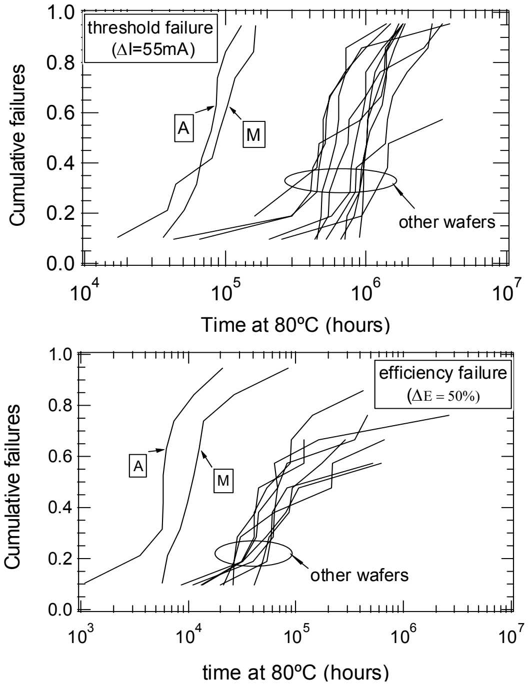

Figure 7: Summary of estimated TTF based on linear fit and extrapolation of 80°C ageing data from unirradiated lasers.

After the gamma and neutron irradiation the lasers were then also aged at 80°C. As with the unirradiated parts the irradiated devices were measured at 20°C at periodic intervals, typically 150-200 hrs. Some typical results are shown for the threshold currents in Fig. 8, with data from AVT 3. The threshold current at 20°C varies little due to the influence of the aging at 80°C, and only the effects of annealing are visible, particularly near the beginning of the ageing. The same comments also apply to the efficiency measurements. The annealing may well have masked wearout effects so we have concluded that a precise measurement of wearout was not possible, however it is expected that the annealing rate was very slow towards the end of the ageing test, so any significant wearout, such as that observed in unirradiated parts from wafers A and M should have still been visible.

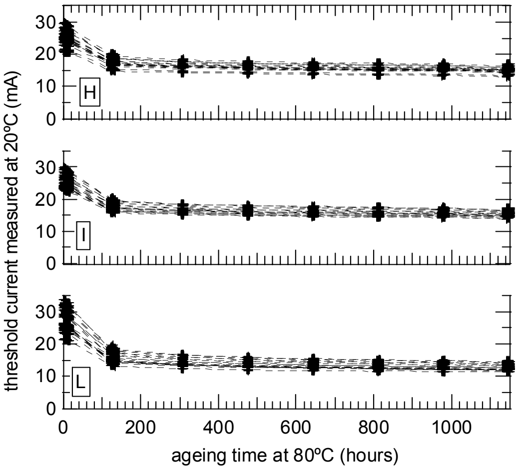

Figure 8: Threshold current in 30 irradiated lasers (wafers H, I and L), measured at 20°C at periodic intervals during aging at 80°C.

IV. PHOTODIODE RESULTS

A. *Radiation damage (AVT steps A and B)*

Measurements of dark-current and responsivity were made in-situ before and during irradiation. There was no visible degradation in terms of leakage current and responsivity in the gamma irradiated devices. The leakage current increase and repsonsivity change, at -5V, versus neutron fluence are shown in Figs. 9 and 10. Overall, the results are very good in terms of the device performance and all three wafers pass the acceptance criteria for responsivity.

After $5x10^{14}n/cm^2$ neutron fluence, the leakage current was at most 10μA and there was little difference between samples from different wafers, after the same fluence. 20% of the leakage current damage annealed in 400hrs. The maximum loss of responsivity at 5V reverse bias was between 8% and 32% across the 3 wafers, with wafer 3 having greatest loss, then wafer 2, and wafer 1 the least. Only 10% of the damage annealed in the 400 hours (at room temperature) following irradiation, as shown in Fig. 9 and no further annealing of the responsivity damage occurred during the subsequent accelerated ageing at 80ºC. Interestingly, the annealing rates for leakage current and photocurrent are not the same. We therefore conclude that the defects responsible for the leakage current increase and loss of responsivity are different, otherwise they would anneal with similar dynamics. The different levels of damage in the different wafers is also expected to be due to the differences between the wafers, rather than an effect of different neutron flux, since a flux dependency usually requires some significant level of annealing (or other defect kinetics) to be occurring during the irradiation.

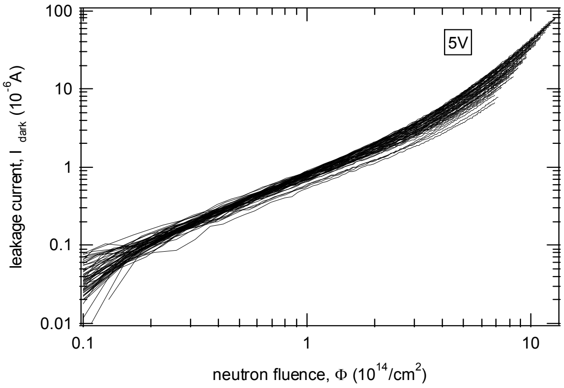

Figure 9: Leakage current damage at 5V reverse bias in all 60 irradiated photodiodes.

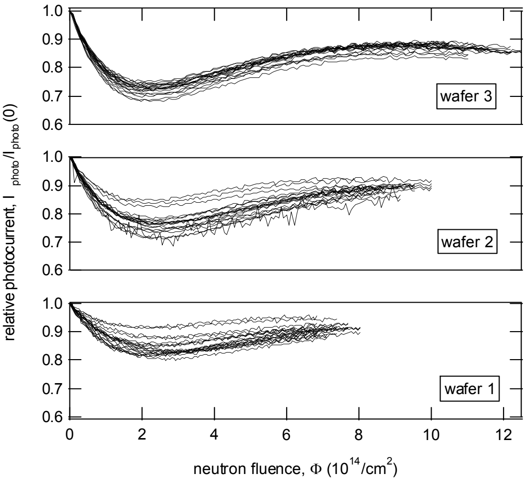

Figure 10: Damage to the responsivity at 5V reverse bias.

B. *Wearout during accelerated ageing (AVT steps C and D)*

The 60 irradiated devices were then aged alongside the 30 remaining unirradiated samples, at 80ºC, for 800 hours, (estimated to be equivalent to 10^7 hrs at –10ºC) under 5V bias and with ~170μW input optical power at 1310nm wavelength. There were no indications of wearout, in terms of either an increase in leakage current or decrease of responsivity, as shown in Figs. 11 and 12. The large spread in the photocurrents in Fig.11 was related to the use of several optical splitters in series (contributing approx. ±10% variation), the initial spread of responsivities (approx. ±10% contribution), and finally the varying amounts of radiation damage (±5%). The only effect observed was annealing of the leakage current damage in the irradiated samples. The unirradiated parts did not exhibit any increase in dark current, at least at the level of ~2nA, which was the sensitivity of the measurements. There was no further annealing of the damage to the responsivity.

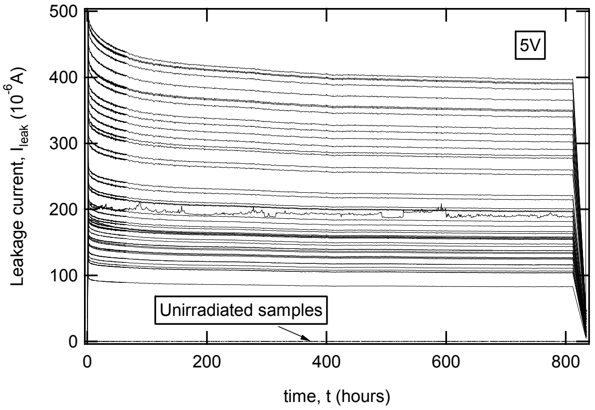

Figure 11: Leakage current at -5V. The temperature was 80ºC for 800 hours, and 20ºC before and after the ageing period.

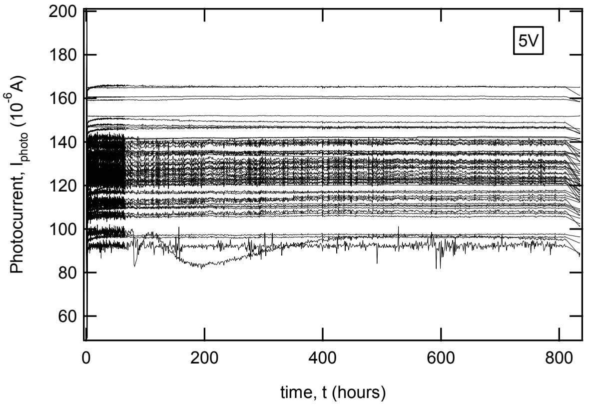

Figure 12: Response at –5V to an optical signal of ~170µW during ageing at 80ºC.

V. SUMMARY AND CONCLUSIONS

CMS optical links require the manufacture of more than 60000 laser transmitters and 4000 photodiodes. The devices must be radiation hard and reliable enough to work for 10 years in an extreme radiation environment.

Both the lasers and photodiodes are based on COTS components, therefore we have established an advance validation test (AVT) procedure to check the radiation hardness and reliability of wafers before mass production takes place. The test procedures are based on those already put in place during earlier stages of the project.

5 AVTs have been performed to date on lasers and one on photodiodes, covering the total nominal quantities of parts ordered for CMS. At least one more AVT is required to cover a spare quantity of lasers.

Concerning the observations made on 390 laser samples taken from 13 wafers (of at least 60000 total devices), all devices passed the AVT. Radiation damage from neutrons increased the laser threshold current by 24mA and decreased the efficiency by 23% on average after 5x10^{14}n/cm^2 (~20MeV neutrons). The damage in each wafer was similar, but from wafer to wafer there were a slightly larger variation. Gamma irradiation caused no significant damage at all. Annealing of the neutron damage is significant over long timescales and much of the observed damage is unlikely to be present over longer irradiation periods, such as during the 10 year lifetime of the devices in CMS. The reliability of the devices is very good in general with device time-to-failure well in excess of the 10-year operational lifetime. Lasers from two of the wafers exhibited much greater degradation than the other wafers and we will try to avoid using lasers from these two wafers in the final optical links.

Concerning the 90 photodiodes tested from 3 wafers, (providing 3600 final parts), all devices passed the AVT. Gamma irradiation had no effect and neutron damaged generated an increase of 10µA in the leakage current and a loss of at most 32% of the responsivity. There were some small differences in radiation sensitivity across the full set of samples, particularly for the photocurrent. There was no degradation due to wearout observed during accelerated ageing.

The AVTs conclude 10 years of environmental testing of parts for the optical links. The test results give great confidence in the radiation hardness and reliability of these parts for the CMS optical links. The experience gained also forms a solid foundation for testing of parts for upgrades to the CMS optical link systems.

VI. ACKNOWLEDGMENT

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