Radiation hardness assurance and reliability testing of InGaAs photodiodes for optical control links for the CMS experiment

K. Gill, M. Axer, S. Dris, R. Grabit, R. Macias, E. Noah, J. Troska and F. Vasey

***Abstract*— A radiation hard 80Mbit/s digital optical link system with 7200 fibre channels is being produced for the CMS Experiment at CERN. A series of tests including radiation damage and thermally accelerated ageing have been made to qualify and assure the radiation hardness and reliability of InGaAs photodiodes intended for use in this system.**

***Index Terms*— photodiodes, radiation hardness assurance, reliability, CMS optical links.**

I. Introduction

DIGITAL optical links will be used in an extreme radiation environment to control several sub-detector systems of the Compact Muon Solenoid (CMS) Experiment [1], [2]. CMS is one of the new generation of High Energy Physics experiments that will operate at the CERN Large Hadron Collider (LHC) [3]. Both CMS and LHC are currently under construction at the CERN Laboratory, with the intention of collecting the first Physics data in 2007.

The control system including the optical link is illustrated schematically in Fig. 1. It uses a token-ring architecture between a master controller at the Front-End Controller (FEC) located in the counting room and Communication and Control Unit Modules (CCUMs), which are arranged in a ring that is located inside the CMS detector.

Clock and control data are transmitted optically at 1310nm, using single-mode fibre cables, from the optoelectronic transceiver (TRX) on the FEC to the front-end digital optohybrid, where they are converted to LVDS electrical signals. These signals are sent electrically around the ring of CCUMs and back to the DOH, where they are transmitted back to the FEC via the optical links. The clock line, which also contains encoded trigger signals, runs at 80Mbit/s and the data line carries control signals at 40Mbit/s. The control link is specified to operate with a Bit Error Rate (BER) less than 10^{-12} and a jitter below 0.5ns. Details and specifications of the system and parts are available in [4].

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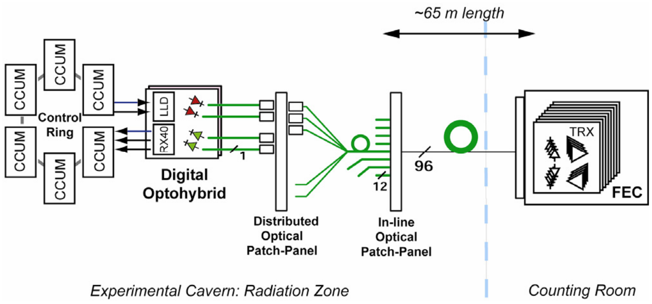

Fig. 1. Control system with digital optical link used in several sub-detectors of CMS.

The electrical ring architecture allows the total number of optical control links to be reduced and only 7200 fibre channels are required service the entire CMS Tracker, Pixel, ECAL, Preshower and muon-RPC sub-systems, which contain a vast number of individual detectors, e.g. 10 million microstrips in the Tracker [1]. The ring of CCUMs and optical links both include redundant clock and data paths in each part, providing protection against failures that would otherwise cause the loss of control of all detectors attached to a given ring.

In this paper we focus on the radiation hardness and reliability of the photodiode components. Fig. 2 shows photodiodes mounted alongside lasers and the corresponding receiver and transmitter ASICs on a final digital optohybrid (DOH) ready for integration into the CMS detector system.

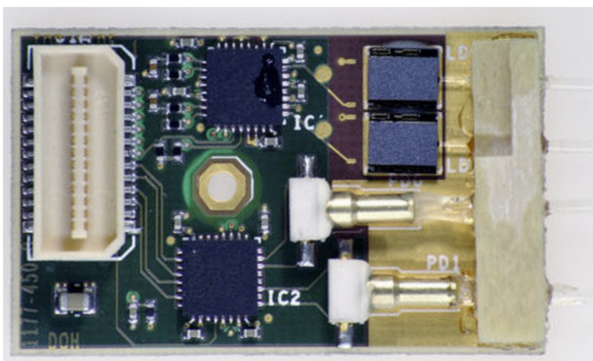

Fig. 2. P-i-n photodiodes (2 Fermionics FD80S8F devices, bottom right) mounted on a CMS digital optohybrid. Above these are two lasers, also subjected to similar assurance tests [5], [6]

The parts located inside CMS will be operated in a severe environment. For example, in the CMS Tracker, which is located close to the beam collision point, the operating environment will include a low temperature (-10°C), high magnetic field (4T), and an intense radiation field. The fluence of particles over the first 10 years of operation is expected to be up to $2\times10^{14}/cm^2$ (dominated by pions with energies around 200MeV), accompanied by a total dose of up to 100kGy [7].

Once integrated into the CMS detector systems, many of the optical link parts will be inaccessible for maintenance or repair. As well as radiation hardness, good reliability is therefore also a key requirements for all link components situated inside the CMS detector systems.

An extensive quality assurance (QA) programme [8] has been followed throughout the optical links project that has addressed functionality, radiation hardness and reliability, plus other QA issues, related to all the components of the links as well as the system as a whole. Figure 3 illustrates the development of the project in terms of the radiation damage and reliability testing of the photodiodes. Between 1996 and 1998 there were a series of validation tests to investigate the radiation hardness of various photodiodes, including both COTS and new prototypes, from different manufacturers [9]. These led to further measurements in 1998-2000 of the radiation damage from different sources, as well as accelerated ageing of irradiated parts, focusing on the suppliers whose parts had performed best in the earlier tests. The aim was to qualify these photodiodes for the final application in preparation for the Tender.

Following a delay during which we focused on launching the production of the analogue optical link system [1], a tender was launched in 2003 and the Fermionics FD80S8F InGaAs/InP p-i-n photodiodes were selected. These are relatively high-speed photodiodes with 80µm active diameter mounted in a very compact package. This diameter allows good coupling of the optical signal whilst keeping a reasonably small cross-section for single-event-upset (SEU) [10].

Small modifications were made to the standard Fermionics COTS part. Corning SMF-28 optical fibre with acryllate buffer, supplied by Ericsson Cables, terminated with MU-connectors, supplied by Sumitomo, were used instead of the standard Fermionics pigtail. The fibre and connectors had already been qualified as being sufficiently radiation resistant by CERN [11]. In addition, the brass ferrule was left un-plated (normally nickel/gold plated) to reduce the force on the package when placed inside the 4T magnetic field inside the CMS Tracker. There are no parts, such as lenses or encapsulation materials, in the optical path within the photodiode that could degrade the radiation resistance [12].

Being based on a COTS part, there were no guarantees of radiation hardness of the photodiodes supplied for the digital optical links. We therefore decided to continue radiation hardness assurance testing into the final production. This was done by means of an ‘advance validation test’ (AVT) [11] which involved radiation and reliability testing of samples from wafers that the manufacturer intended to use to produce the final photodiode receiver assemblies. The AVT allowed CERN to accept or reject these wafers before the final production was started. The test procedures for the AVT were based closely on those used during the earlier prototype validation [9].

Altogether, the data from the sample validations and subsequent AVT presented in the following Sections add significantly to the results of our earlier tests on devices from other manufacturers [9], [13], [14] and extend to higher fluences the body of data from previous studies, for example [12], [15]-[18], where tests of InGaAs photodiodes have been made for space and nuclear applications. The AVT represents the first time that so many InGaAs photodiodes of the same type have been tested to such high particle fluences and doses. The studies presented here have not attempted to cover all points of interest addressed elsewhere, for example the types of defect being created by radiation damage [15], [16], non-ionizing energy loss (NIEL) [16], [17], or susceptibility to SEU [10], [18]. We have instead focused pragmatically on the areas of greatest importance to the CMS optical links project, namely response to different types of particle radiation at high fluences and doses, and the suitability of the intended final photodiodes for our application, in terms of the main effects of radiation damage and wearout (i.e. leakage current and responsivity) that could influence the CMS control link operation.

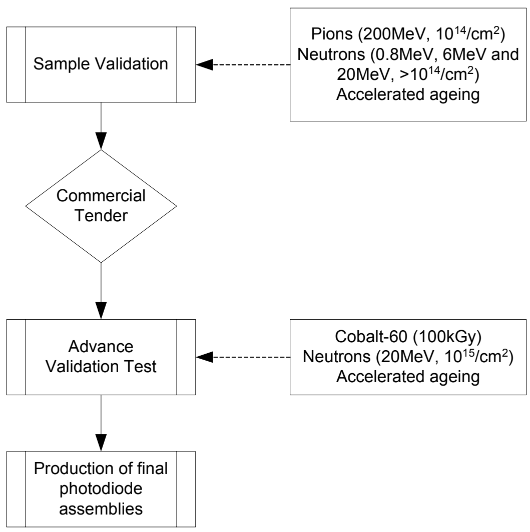

Fig. 3. Radiation hardness and reliability test programme for p-i-n photodiodes to be used in the CMS digital optical control links.

II. Sample Validation

During sample validation, 40 Fermionics FD80S8F photodiodes were taken from different lots of the manufacturer’s standard parts stock, and subjected to functional, radiation damage and reliability tests. For all the parts tested, the pre-irradiation characteristics at 5V reverse bias included leakage currents less than 100pA and a responsivity of approximately 0.85A/W.

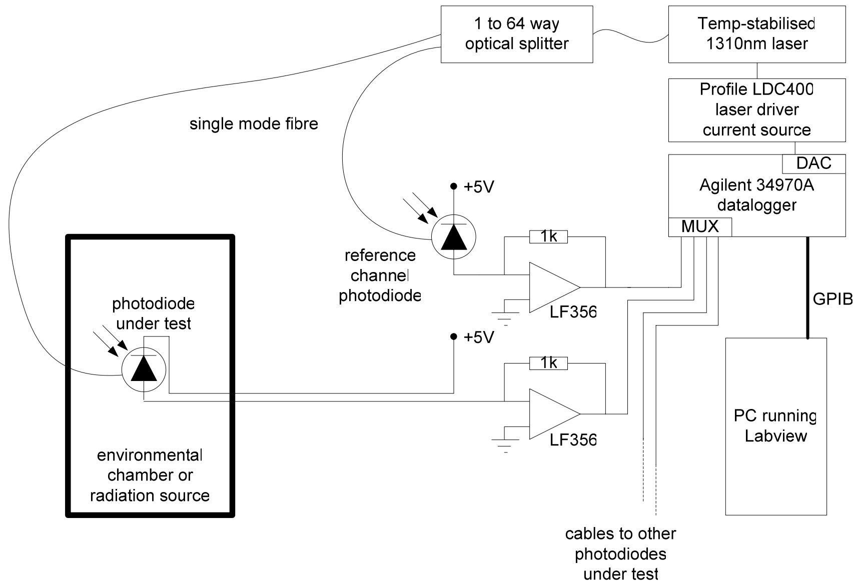

Fig. 4: Experimental setup for in-situ measurement of photodiode leakage current and responsivity during ageing or irradiation. Only one photodiode under test is shown, whereas up to 60 devices were tested in parallel using this system.

The photodiodes were exposed to different radiation sources: 200MeV pions at PSI, Villigen, Switzerland, 0.8MeV neutrons at PROSPERO, CEA Valduc, France, ~6MeV neutrons at SARA, ISN Grenoble, France and ~20MeV neutrons at CRC, Louvain-la-Neuve, Belgium. Gamma tests were omitted since in tests on other devices from other manufacturers the ionisation damage was negligible. (Gamma tests were made later during the AVT on Fermionics parts, when no damage was again observed.) The pion source was used since these particles will be the most important species inside the CMS Tracker and Pixel systems, where the radiation flux is greatest. Finally, neutron sources were used because they are more readily available than the pion beam, and more devices could be irradiated simultaneously. The ~20MeV neutron source at CRC was used again later for the photodiode AVT.

Irradiation using these particle beams caused a large increase in dark-current (or leakage current) and some loss of responsivity through displacement damage [19]. This type of damage is understood to introduce defects into the crystal that in turn introduce energy levels that are normally forbidden in the semiconductor band-gap. These levels can increase leakage currents through charge generation, and act as trapping and recombination centres for the photo-generated signal charge, thus affecting the responsivity. [19]

Measurements of photocurrent and leakage current were made in periodic cycles, in-situ, using the setup shown in Fig. 4. The current in an external laser was increased in steps to increase the light power in steps at the photodiodes from 0 to 250μW. The dc photocurrent was recorded at each step after 1s of settling time. The reference optical channel allowed for correction of any unwanted variations in light levels at the photodiodes, though the fluctuations were very small from cycle to cycle. The leakage current was then measured with the external laser switched off. The photocurrent and leakage current measurements were accurate and reproducible to a level better than 1% for currents above 1μA and at smaller currents the precision was limited by the resolution of the datalogger which was ~10nA.

The leakage current damage, measured at 5V reverse bias, is shown for the Fermionics photodiodes in Fig. 5. The measurements were made at ambient room temperature and then corrected to 20°C. After irradiation to fluences of 2×10^{14}pions/cm^2, which is typical of the worst-case in the CMS Tracker [1], the leakage current is expected to be around 10μA.

There was one photodiode where the leakage current damage was much worse than the others and this device was considered to be an anomalous case. Photodiodes from another manufacturer (Epitaxx) with the same active area were also irradiated at the PSI pion source (and with 6MeV neutrons) in earlier studies [9], [13] under the same conditions to the Fermionics parts. The leakage current damage in the Epitaxx parts matched the leakage current increases of the three Fermionics photodiodes where the results were similar under pion damage.

As in our earlier tests on similar photodiodes from different manufacturers, there was relatively little annealing of the leakage current damage. This will be illustrated again later in the AVT results, where a large amount of post-irradiation data was collected.

Since the amount and rate of annealing was not large, the different radiation sources can be compared by checking the fluence where the leakage current reaches a certain value. This method allows a comparison of the damage even when the damage evolution is non-linear, as with the photodiodes.

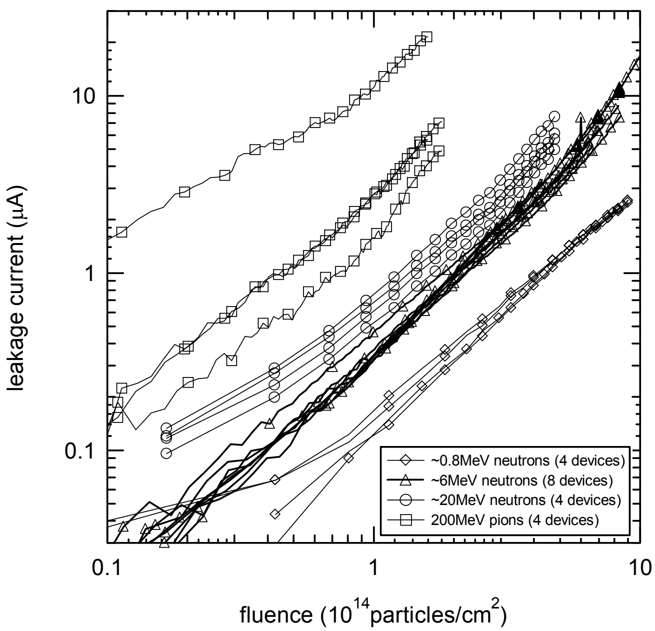

Fig. 5. Damage to leakage current at 5V reverse bias at different irradiation facilities for all parts tested during sample validation.

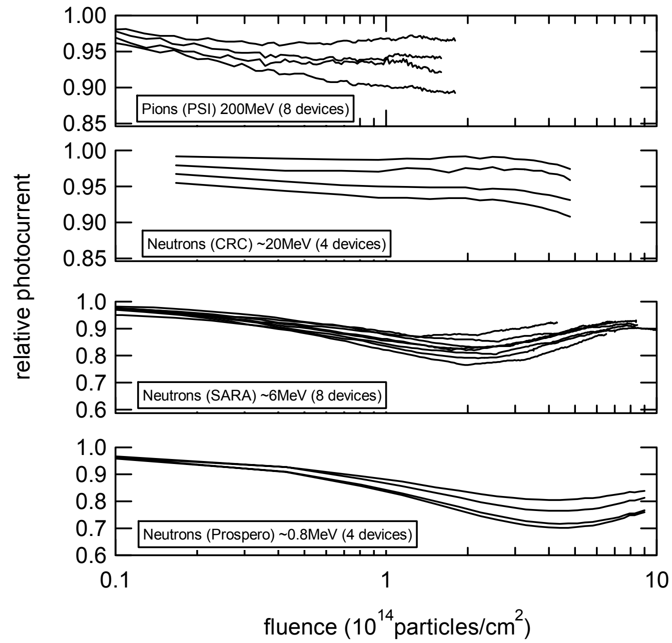

Fig. 6. Damage to photodiode responsivity at 5V reverse bias at different irradiation facilities for all parts tested during sample validation.

Taking 1μA of leakage current damage as an example, the pions appear to be ~2.3 times more damaging than the CRC neutrons (~20MeV), ~4 times more damaging than the SARA neutrons (~6MeV) and approximately 7 times more damaging than the Prospero neutrons (~0.8MeV). The difference in damage is expected to be related to the increased atomic recoil energy, with increasing incoming particle energy, in the displacement damage events [13]. A full non-ionizing energy loss (NIEL) [19] analysis was beyond the scope of the qualification though this remains a possible area for future activity.

Photocurrent measurements were made with up to 250μW of light power at 1310nm incident on each photodiode. The results for the relative change in photocurrent, effectively the same as the responsivity change since the photocurrent was linear with input power in this range, are shown during irradiation in Fig. 6. We recall that the typical pre-irradiation value of responsivity was 0.85A/W.

The evolution of the damage appears to be complicated and the underlying mechanism is not yet understood. For the Fermionics photodiodes (and some other types of photodiode where the p-side is the illuminated side) the damage to the responsivity often has the form that has been sketched in Fig. 7 [9]: there is some initial loss of response (region A), that recovers by some amount at intermediate fluences (region B) before the loss increases again (region C).

At first sight, the data shown in Fig. 6 appears to indicate that the 0.8MeV neutrons are the most damaging, since the overall losses are the highest. However, the actual conclusion is not so clear since, in most cases of the photodiodes irradiated with the 200MeV pions and ~20MeV neutrons, the damage has progressed through the intermediate stage (region 'B') and was just beginning to move into the next stage (region 'C') where the damage begins to increase again.

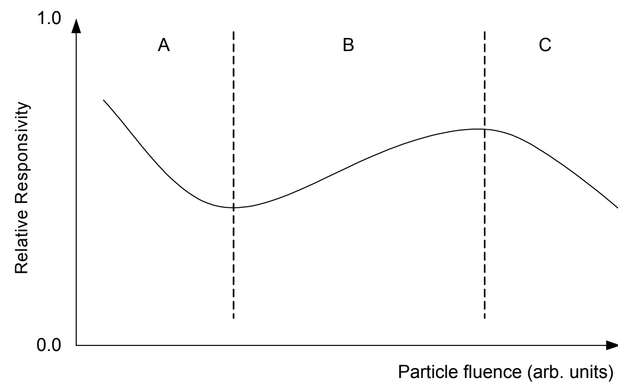

Fig. 7. Typical dynamics of responsivity change under particle irradiation for Fermionics photodiodes.

In contrast the devices irradiated with the 0.8MeV neutrons are only just entering the region 'B' at the end of the irradiation, which was to a significantly higher fluence. Therefore it could be argued instead that the devices irradiated with the 200MeV pions and ~20MeV neutrons were more damaged, after a given fluence, than those irradiated with ~0.8MeV neutrons. In this respect, the pions are also more damaging than the ~20MeV neutrons, as there are some indications that the region 'C' is entered close to $1x10^{14}$pions/cm^2, compared to around $3x10^{14}$(~20MeV neutrons)/cm^2. The data from the SARA neutrons (~6MeV) are positioned between those from the other two neutron sources, as with the leakage current damage.

Another interesting result was that the damage in region 'A' was so different in the parts irradiated with different sources. It is expected that this effect was not related to the particle flux since there is very little annealing of the responsivity damage. (The annealing is shown later for the AVT results where there were better statistics.) Instead, it was concluded that the differences in the minimum response seen in region 'A' for the different radiation sources were in fact due to wafer-to-wafer variations in the Fermionics parts. The devices irradiated with 20MeV neutrons and 200MeV pions were all from a later batch (and different wafer) compared to the devices irradiated with the SARA and Prospero neutron sources. There was also a clear variation between devices from different wafers measured later in the AVT.

Concerning the reliability of the photodiodes, Fermionics have qualified their product [20] according to Bellcore standards [21]. Additional ageing tests were also made on irradiated samples at CERN. 20 photodiodes were irradiated with 10^{15}n/cm^2 (~0.8MeV neutrons at Valduc) and then operated at 80ºC for 2000 hours, under 2V reverse bias and 150µW illumination. No effects of wearout were observed, in terms of any increase in leakage current or change in responsivity, as in earlier studies from other manufacturers [14]. Wearout is normally a thermally activated process [22] and the activation energy is expected to be around 1eV [23]. An accelerated ageing period of 2000hrs at 80°C is therefore expected to be equivalent to ~10^7hrs operation at –10°C, the temperature inside the CMS Tracker.

It should be noted that variations in dc signal level and signal modulation amplitude in the optical links could, in any case, be caused by other influences in the system apart from radiation damage to the photodiodes. For example, the laser transmitter dc power offset and output optical signal amplitude will most likely be different in different laser channels, and there will, in addition, be a variable amount of loss in the optical fibre and connectors from channel-to-channel.

To compensate for these differences, along with the effects of radiation damage on photodiodes in the CMS control links, the RX40 ASIC [24] that receives and processes the signals from the photodiodes on the DOH was designed specifically to normalize both variations in signal amplitude (designed to work for amplitudes down to 10µW, where a cut-off-is applied in the RX40) and dc current (up to 500µA).

In summary, the series of radiation damage and reliability tests during sample validation qualified the Fermionics photodiodes as sufficiently radiation resistant and reliable for use within CMS, even if the precise dynamics of the evolution of the displacement damage have not been understood. All of the known effects affecting the component or system performance have subsequently been taken into account in the definitions of the specification of the digital optical control link system and component parts [2].

III. AVT FOR RADIATION HARDNESS ASSURANCE

As mentioned in the Introduction, the photodiodes are essentially COTS parts and as such there was no guarantee of continued radiation resistance and reliability after irradiation. Prior to the final production of the photodiodes, samples from three wafers were therefore passed through the advance validation test (AVT) to provide assurance that they were sufficiently radiation hard and reliable. These wafers were intended for production of the final order of 3600 photodiodes with possible spares. The samples were packaged in the intended final form for CMS.

The AVT procedure is illustrated in Fig. 8. Ninety samples in total were tested in the AVT, of which 60 were irradiated. The same measurement setup was used as that described for the earlier tests. The acceptance criteria for the AVT were such that the dark current in the irradiated photodiodes should be less than 500µA at –5V after 100kGy gamma dose and $5x10^{14}$n/cm^2 (20MeV) neutron fluence. Based on the measurements presented in the previous section, this fluence is equivalent to $2x10^{14}$pions/cm^2 (with energies around 200MeV [1]), the worst-case fluence expected inside CMS. In addition, the photodiode responsivity should remain above 0.4A/W at –5V up to the same dose and fluence.

After accelerated ageing at 80°C for 1000 hours, the dark current at 20°C and –5V should less than 500µA for the irradiated samples and less than 5nA for the unirradiated devices. The responsivity should remain above 0.4A/W at –5V during ageing of the irradiated samples, or 0.75A/W for unirradiated samples.

In all, 95% of the photodiode samples from each wafer must pass these criteria in order for the entire wafer to be accepted. Essentially only one device is allowed to fail per wafer. Should more than 1 device fail, the corresponding wafer would be rejected and a new lot of devices taken from a different wafer.

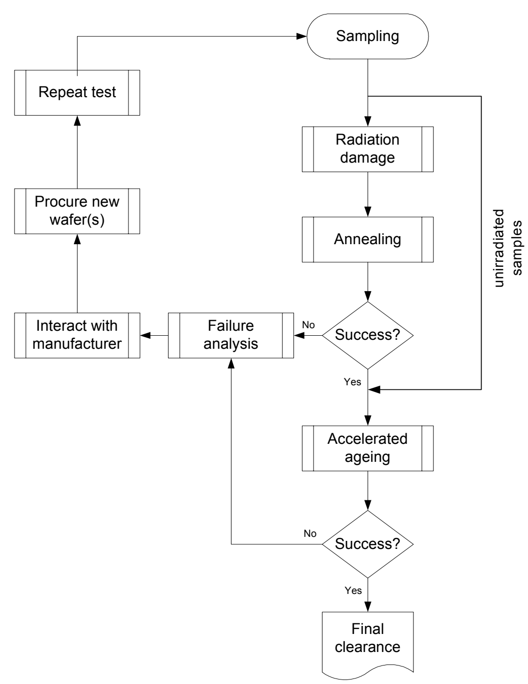

Fig. 8. Flow chart of the AVT procedure for radiation hardness and reliability assurance of photodiodes.

It should be noted that there was, in general, a very large safety margin built into these tests of radiation hardness. This is because only a small fraction (<10%) of the photodiodes in the final system, i.e. those used for the Pixels and innermost Tracker layers within CMS, will actually be exposed to the levels of radiation used in the AVT. The charged particle flux in CMS, up to the ECAL, decreases with increasing distance from the centre of CMS (with approximately 1/radius^2), and there is also a background of neutrons scattered from the calorimeters (10^{13}n/cm^2 total fluence in the first 10 years) that dominates the radiation field at the outer radius of the Tracker volume. As such, most photodiodes will see much lower total fluences and doses than those used in the AVT.

A. Radiation damage and annealing

Gamma irradiation was done using ^{60}Co gammas at SCK-CEN. The total gamma dose was 100kGy ±10%, verified with PAD dosimeters. The dose was uniform across the samples and the dose rate was stable over the irradiation period of 48hrs. The irradiation was carried out at 30°C.

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 except for a ~5% loss of responsivity, which was probably due to darkening of the 2m long fibre pigtail under gamma irradiation. The radiation damage to the fibre had been checked previously using the same ^{60}Co source, in an AVT of raw fibre that preceded the manufacture of the final terminated fibre pigtails.

The same set of photodiodes were then irradiated with 20MeV (mean energy) neutrons at CRC. The target neutron fluence was $8x10^{14}$/cm^2 and the actual fluences received were between $7x10^{14}$/cm^2 and $1.4x10^{15}$/cm^2. These values are in excess of the fluence required to validate the parts, which allowed the possibility of observing the damage behaviour also at higher fluences.

The actual fluence was determined by measuring the distance of the sample from the neutron beam source, combined with a previous calibration of the flux versus distance [25] for a given cyclotron beam current. The irradiation was carried out over a period of 21 hours, at a temperature of 25-28°C.

Using the test-setup shown earlier in Fig. 4, measurements of dark-current and responsivity were made in-situ before and during neutron irradiation and then for 400 hours following irradiation to monitor any annealing.

The leakage current increase versus neutron fluence is shown in Fig. 9 at 5V reverse bias. After $5x10^{14}$n/cm^2 neutron fluence, the leakage current was at most 10μA. There was a small difference between samples from different wafers, after the same fluence but this does not affect significantly the outcome of the AVT. Approximately 20% of the leakage current damage annealed in 400 hours after the irradiation at 21-23ºC, as shown in Fig. 10. Since the temperature dependence of the annealing is not known, it was not possible to extrapolate these data to the conditions expected in the CMS Tracker. However, we can assume that, in the worst case, the damage during CMS operation would be the same as that measured here after $5x10^{14}$n/cm^2 without annealing, i.e. 10μA.

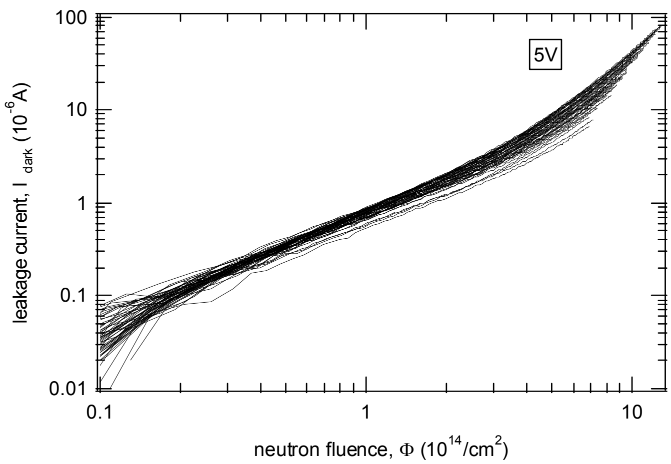

Fig. 9. Leakage current damage at 5V reverse bias in all 60 irradiated photodiodes.

The effect of neutron damage on the responsivity is shown in Fig. 11. Overall, the results were very good in terms of the device performance and all three wafers passed the acceptance criteria for responsivity. The greatest loss of responsivity in each photodiode, at 5V reverse bias, was between 8% and 32%. This corresponds to a minimum responsivity of around 0.6A/W. Wafer 3 had the greatest loss, then wafer 2, and wafer 1 the least.

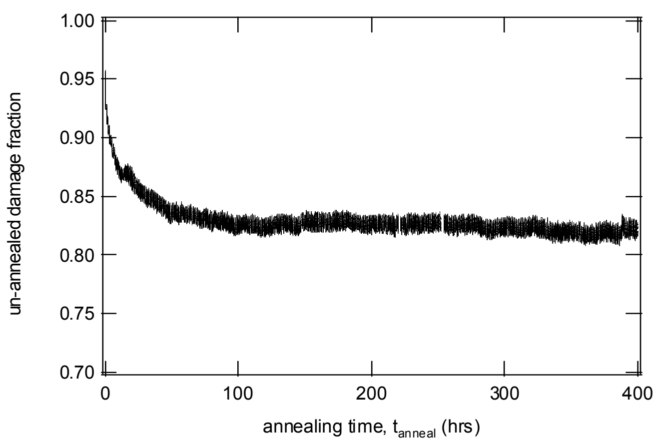

Fig. 10. Annealing of the leakage current at 5V reverse bias after irradiation. Data from the 20 photodiodes sampled from wafer 3.

Only 10% of the responsivity damage measured at the end of irradiation annealed in the 400 hours (at room temperature) following irradiation, as shown in Fig. 12, and the annealing appears to already be reaching a limit during this period. Interestingly, the annealing rates for leakage current and photocurrent are not the same, which suggests that the defects responsible for the leakage current increase and loss of responsivity are different, otherwise the damage should anneal with similar dynamics.

The different levels of responsivity damage between the three wafers were expected to be due to the differences between the wafers, rather than an effect of different neutron flux. Usually, a flux dependency requires some significant level of annealing (or other defect kinetics) to be occurring during the irradiation.

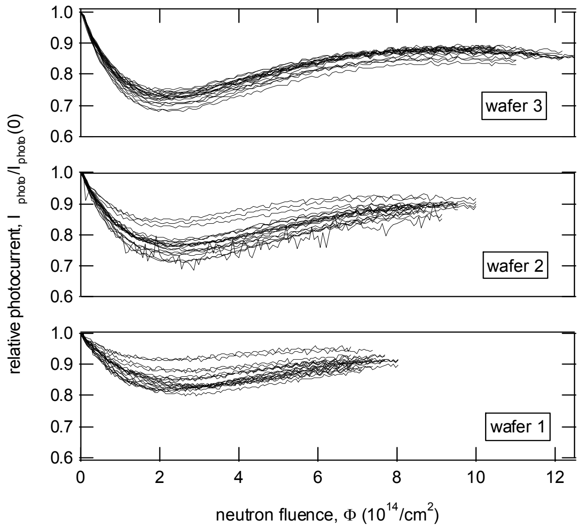

Fig. 11. Damage to the responsivity at 5V reverse bias in all 60 irradiated devices (20 per wafer).

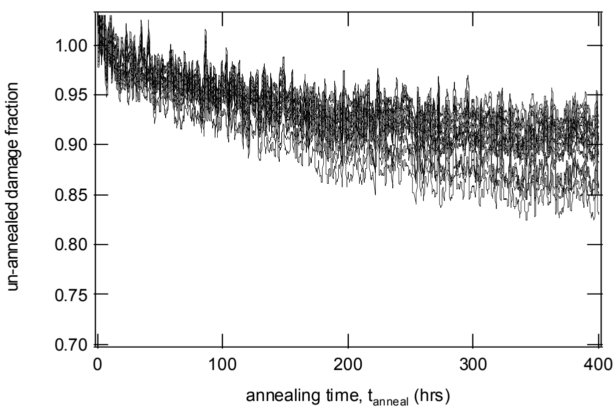

Fig. 12. Annealing of the damage to the responsivity at 5V reverse bias. Data from the 20 photodiodes sampled from wafer 3.

B. *Accelerated ageing*

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. In-situ measurements were again made at periodic intervals with the same test setup shown in Fig. 4.

There were no indications of wearout as shown in Figs. 13 and 14. Wearout is expected to cause an increase in leakage current or decrease of responsivity. For the leakage current, the only effect observed during ageing was some continued annealing of the damage in the irradiated samples. The unirradiated parts did not exhibit any increase in dark current, at least at the level of a 10nA, which was the limit of the sensitivity of the measurements. The large spread of leakage currents amongst the irradiated devices reflects only the different levels of radiation damage in each part, combined with the effect of increasing the temperature, which magnifies these differences since the dark current increases strongly with temperature [16].

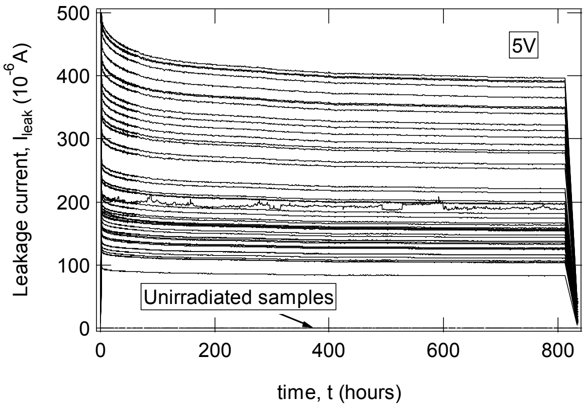

Fig. 13. Leakage current at 5V in all 90 devices in the AVT. The temperature was 80 º C for 800 hours and 20 º C before and after the ageing period.

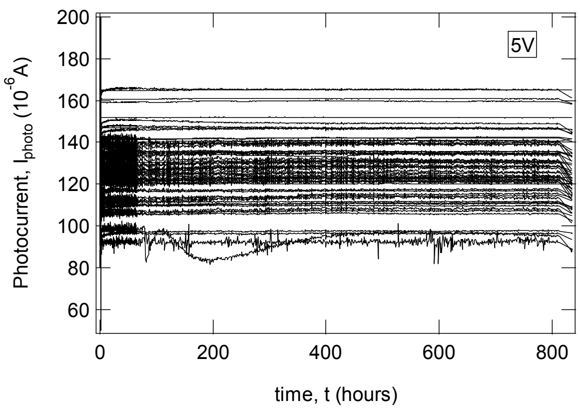

Fig. 14. Response at 5V reverse bias to an optical signal of ~170µW for all 90 devices in the AVT. The temperature was 80 º C for 800 hours and 20 º C before and after the ageing period.

For the photocurrent results, apart from one device that shows some instability during the first half of the ageing, the only apparently significant feature is the large spread in the photocurrents and this is simply related to the combined effects of using 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%). There was no further annealing of the damage to the responsivity, unlike the leakage current. This is consistent with results from an earlier irradiation/ageing study we made on similar photodiodes from another manufacturer [14].

IV. CONCLUSION

Fermionics InGaAs/InP FD80S8F photodiodes have been qualified as sufficiently radiation hard and reliable for use in the CMS digital control optical links, capable of operating for 10 years in a severe radiation environment.

The radiation hardness and reliability of the final photodiode wafers was also confirmed in an advance validation test before production of final parts was started.

This work concludes a long and extensive study of radiation damage effects in photodiodes for the CMS optical control link system and forms the basis of the future programme of tests for the upgrade of this system.

Acknowledgment

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