Available on CMS information server

CMS NOTE 1997/102

File Name : cms_note.mac.eps
Title : (Adobe Illustrator (R) Version 5.0 Full Prolog)
Creator : Adobe Illustrator(r) 6.0
CreationDate : (3/7/1994) ()

August 1997

Neutron, proton and gamma radiation effects in candidate InGaAs p-i-n photodiodes for the CMS tracker optical links

J. Troska

Blackett Laboratory, Imperial College, London SW7 2BZ.

K. Gill, R. Grabit, F. Vasey

CERN, CH-1211, Genève 23, Switzerland.

Abstract

InGaAs p-i-n photodiodes will be used in the CMS tracker to receive the digital timing and control signals transmitted from the Front End Controller (FEC) boards by 1310nm wavelength lasers. These devices should be sufficiently rad-hard to survive the fluences/doses encountered in the tracker during a ten year operational period. Candidate p-i-n diodes have been irradiated, in a fully packaged, fibre-pigtailed form, with up to 10^{15}neutrons/cm^2 ($<E_n>$=6MeV), 4x10^{14}protons/cm^2 (E_p=24GeV) and 100kGy ^{60}Co photons. Displacement damage from the neutron and proton irradiation caused the leakage current to increase by 6-7 orders of magnitude and the responsivity to decrease by 90% after ~10^{14}p/cm^2 or 10^{15}n/cm^2. Gamma damage was almost negligible in comparison.

1. Introduction

Components of the CMS optical data links[1] for transmission of analogue data and digital timing, trigger and control signals must be both sufficiently reliable and radiation resistant to last ten years of operation. Induced radioactivity inside the experiment, plus the overall complexity of the apparatus, will not permit extensive maintenance, or replacement, of the optical link components. In this note we present radiation damage results for a candidate p-i-n photodiode type that could be used to receive timing and trigger information, as well as digital control signals, in the CMS tracker. The effects of radiation damage on the lasers, to be used as transmitters in the analogue optical links that transfer the signals from the microstrip detectors, is summarised in another note[2].

Several reports of radiation damage in InGaAs p-i-n detectors similar to the type investigated here exist in the literature[3-9], mainly related to the use of opto-electronic components in space satellite applications where the radiation doses encountered (made up of protons, electrons and a low flux of heavy ions) are typically 10^3-10^6Gy, depending upon the length of the mission, the altitude and inclination of the orbit, and the amount of shielding used[9]. Inside the CMS tracker, the atomic displacement damage due the large flux of hadrons is found to be more important. The hadron fluence over ten years of LHC operation, at a distance of 20cm from the beam axis, consists of $\sim 10^{14}$(1MeV neutrons)/cm^2 and $\sim 1.8 \times 10^{14}$ charged hadrons (80% pions, 10% protons, 10% kaons)/cm^2 with energies in the range of several hundred MeV[10-13]. Total dose over 10 years, at 20cm from beam axis, is expected to reach 100kGy[10-13].

2. Experiment

2.1. Devices

The p-i-n detectors tested were back-illuminated, planar photodiodes of 75µm active diameter manufactured by Epitaxx. A schematic cross section of the devices is shown in fig.1[6,14]. The active region (for wavelengths $950<\lambda<1650$nm) is a 3µm nominal thickness epitaxial layer of $In_{0.47}Ga_{0.53}As$ grown on an InP substrate. At 1310nm wavelength, the (1/e) absorption length in $In_{0.47}Ga_{0.53}As$ is ~0.5µm[15]. The InP substrate and cap layer are transparent to light with a wavelength $\lambda>920$nm due to the larger band-gap (1.35 eV compared to 0.75eV in $In_{0.47}Ga_{0.53}As$); the InP cap layer also reduces the dark current generated at the surface[14]. The pre-irradiation leakage current of the p-i-n diodes was <50pA (at 10V reverse bias) and the initial responsivity at 1310nm was typically 0.9A/W[16].

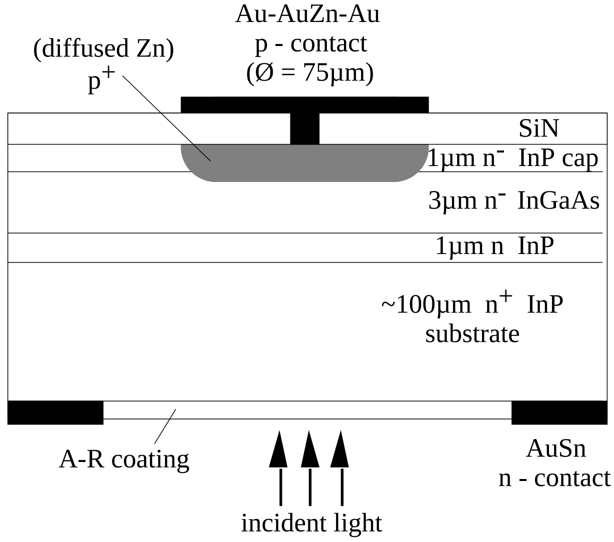

Fig. 1: Schematic cross-section of Epitaxx InGaAs p-i-n photodiode

The p-i-n diodes were obtained in a fibre-pigtailed form from Italtel. The bare p-i-n diodes (600µm x 600µm chip area) are soldered onto a $3x1.5x0.5mm^3$ silicon submount, as shown in fig.2. A single-mode fibre pigtail is stripped and inserted into a v-groove anisotropically etched into the silicon submount. The v-groove aligns the fibre and its end facet reflects the output light into the detector. The fibre is glued into place with epoxy. The optical sub-assembly is then mounted in a hermetically sealed, ceramic 8-pin Dual In-Line (DIL) package. Table 1 outlines the number of devices irradiated and the fluence/dose received by each device.

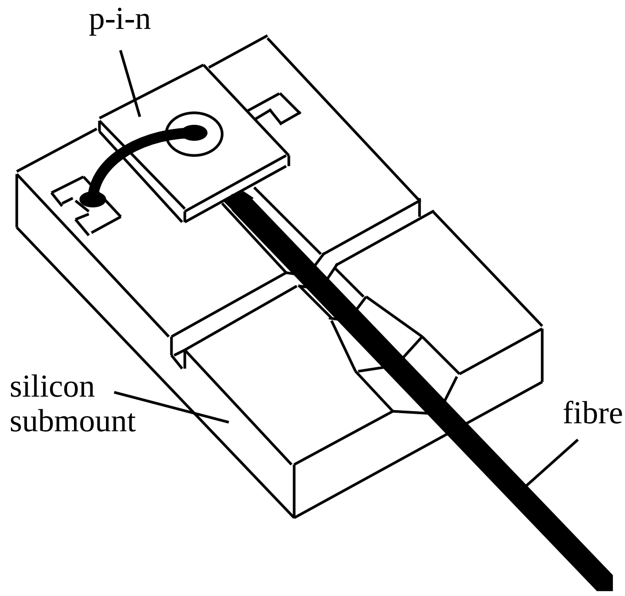

Fig. 2: P-i-n photodiode mounted on silicon sub-mount.

Table 1: devices and radiation dose/fluence

Device	n-fluence ($10^{14}/cm^2$)	γ-dose (kGy)	p-fluence ($10^{14}/cm^2$)	Device	n-fluence ($10^{14}/cm^2$)	γ-dose (kGy)	p-fluence ($10^{14}/cm^2$)
1	4.0	-	-	8	-	100	-
2	4.7	100	-	9	-	100	-
3	6.0	100	-	10	-	100	-
4	7.8	-	-	11	-	-	4.0
5	10.2	-	-	12	-	-	4.0
6	-	100	-	13	-	-	4.0
7	-	100	-	14	-	-	4.0

2.2 Irradiation conditions

2.2.1 Neutrons

Devices 1-5 were irradiated with neutrons to fluences up to $\sim 10^{15}n/cm^2$, at the ISN SARA facility[17] in Grenoble. Fig.3 schematically illustrates the experimental arrangement. The photodiodes were arranged in front of the beryllium target, which strips off neutrons from a beam of deuterons. The average energy of the neutrons was 6MeV. The neutron fluence was measured by activated foil dosimetry (using 4mm diameter Ni foils) with the different fluences given in Table 1. The absolute accuracy is ~15% due to a systematic uncertainty in the activation cross-sections, but fluence measurements are typically reproducible to within a few percent. A dosimetry foil was affixed to each device. By measuring the integrated beam current at the target the time-stability of the neutron source was checked at 30 minute intervals during the irradiation; the current was almost constant over the irradiation period of ~102 hours. The temperature in the source cell and control room was monitored but not controlled; it was around 18°C during the test with ±2°C maximum fluctuations in the source cell, and 18±4°C in the control room.

The p-i-n diodes were connected via an optical fan-out (shielded in a polyethylene box) to an 8-way fibre ribbon that transferred light, via a splitter, from a 1310nm laser located in the control room. The devices were monitored for ~100 hours before irradiation, 102 hours during the irradiation, and a further 1500 hours (~2 months) after irradiation to measure any annealing. At ~40 minute intervals, measurements were made of the diode leakage current and the response to optical signals (ramped between 0 and ~200µW) were measured at five different reverse bias voltages (0, 2.5, 5, 7.5, and 10V). Another p-i-n photodiode situated in the control room, but connected via the splitter to the same laser as the p-i-n diodes under test, was used to monitor any fluctuations in the laser output characteristics (for example, due to temperature variation). During the idle period between measurements, ~25 minutes of the 40 minute period, all the p-i-n diodes were biased at -5V to simulate typical operating conditions.

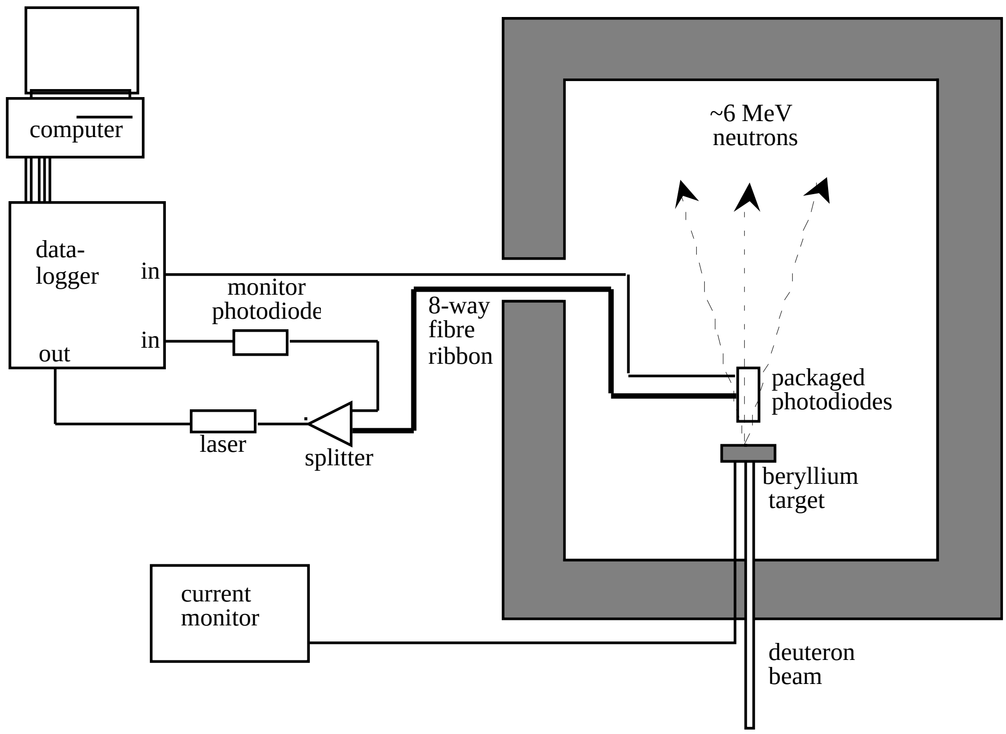

Fig. 3: Schematic experimental arrangement for the neutron irradiation test.

2.2.2 Gammas.

Gamma irradiation of devices 2, 3, 6-10 was carried out at the ^{60}Co source of Imperial College. The photodiodes were mounted on PCB cards that were placed in the centre of the four ^{60}Co source rods. Dosimetry measurements were carried out using several alanine dosimeters placed close to the p-i-n diodes. The total absorbed dose of the p-i-n diodes was 100kGy (±10%), received at a uniform rate over ~77 hours. The irradiation was carried out at room temperature, 20.3±1°C in the source room and 23±2°C in the control room.

The experimental arrangement was very similar to that employed in the earlier neutron test. The photodiodes were illuminated by a laser located in the control area outside the source room. The characteristics of all of the p-i-n diodes (except for devices 9 and 10) were monitored during the irradiation and then for a period of 64hrs after irradiation to measure any annealing. The measurement cycle was similar to the one used in the neutron irradiation, except that the cycle time was 60mins. Due to a technical problem the photodiodes were not measured under bias for the first 52 hours of the irradiation period. This problem was fixed and the p-i-n diode leakage current and response were subsequently measured at 0, 2.5, 5, 7.5 and 10V, with the diodes reverse biased at 5V during the idle period between measurements. In spite of this problem, it was apparent from the results that the bias was not an important factor in the gamma damage up to the dose reached.

2.2.3 Protons

Four previously unirradiated p-i-n photodiodes (devices 11-14) were irradiated with 24GeV protons at the CERN proton synchrotron (PS). Dosimetry was carried out using 9mm^2 aluminium foils by measuring the amount of radioactive ^{22}Na in the foil after irradiation. A fluence of 4.0x10^{14}p/cm^2 (±6%) was measured at the p-i-n diodes, following an irradiation period of 10 hours. The proton beam operated continuously during the irradiation period with the following characteristics: a 14 second cycle time with 3 proton spills of ~2s duration per cycle, with ~$2x10^{11}$p/cm^2 per spill. The temperature environment in the irradiation zone was very stable at 26.7±0.2°C during the irradiation and recovery period.

The experimental arrangement was again very similar to the neutron and gamma tests, except that the monitoring photodiode (used to measure any fluctuations of the laser power) was placed, along with the laser, close to the devices under test (but outside the beam). The p-i-n diode leakage current and response were measured at 30 minute intervals and the devices were reverse biased at 5V between measurement cycles. The devices were left in the beam zone, but outside the beam, after the irradiation, for 1 month, to monitor the annealing behaviour.

3. Results

3.1 Leakage current.

The leakage currents measured at 2.5, 5, 7.5 and 10V reverse bias is shown as a function of fluence in fig.4 for neutron and proton damage. In both cases there is a non-linear increase, of 6-7 orders of magnitude compared to pre-irradiation values, in the leakage current after fluences of $4x10^{14}$p/cm^2 and 10^{15}n/cm^2. If the fluence required to cause a particular current increase is used to determine the relative damage of neutrons and protons, the 24GeV protons are found to be ~10 times more damaging, consistent with the protons introducing around 10 times more defects for a given fluence.

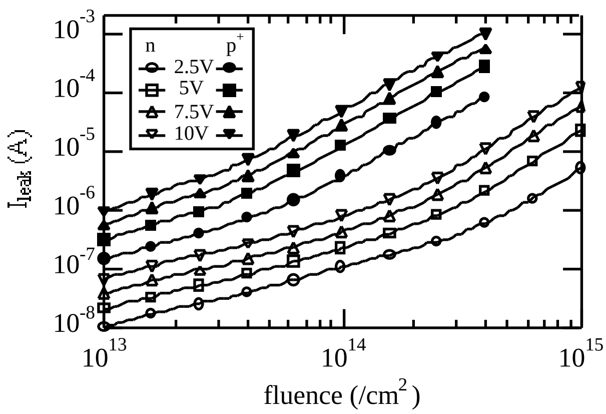

Fig 4: Leakage current increases under neutron and proton irradiation.

In contrast to the hadron irradiation results, devices that were irradiated with ^{60}Co gammas to 100kGy showed a much smaller increase in leakage current. This is illustrated in fig.5 which shows I-V curves measured before and after (only) gamma irradiation. Some devices had been previously irradiated with neutrons to ~$4x10^{14}$n/cm^2 and there was no significant additional damage due to gamma irradiation.

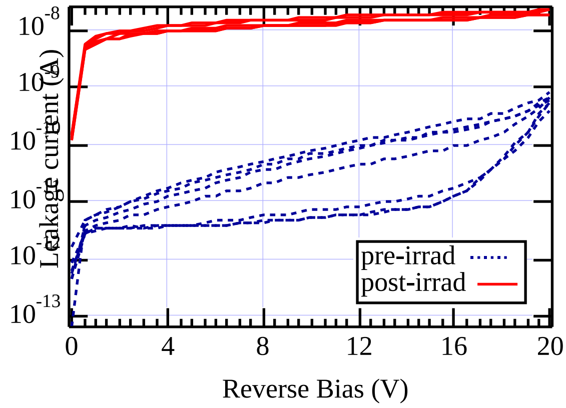

Fig 5: I-V characteristics for devices before and after gamma irradiation.

The increase in leakage current following gamma irradiation had actually reached a saturation value long before the final dose was reached, indicating that this effect was probably not related to displacement damage, which normally causes a steady increase in current. An alternative possibility is that this leakage current increase is caused by ionisation damage in the passivation layer (a SiN layer on top of the InP cap) or at its interface with the diode.

Since the overall increase in leakage current due to gamma damage is much smaller than that due to typical LHC hadronic fluences, ionising damage will therefore be only a negligible factor in determining the leakage current in these p-i-n diodes if they are used inside the CMS tracker. The ionising dose due to the received proton flux is similar to the total dose of 100kGy received during the ^{60}Co gamma irradiation. The low degree of leakage current due to ionising damage thus supports the argument that the different damage rates of the neutrons and protons are not related to the additional charge of the proton, but mainly to the energy difference of the sources.

Annealing of the leakage current was also measured after each irradiation test. For the gamma irradiated devices no significant recovery was observed. Fig.6 illustrates the change in leakage current during the first 800 hours after neutron irradiation. It is clearly apparent that the degree of recovery is small with only 20% of the initial damage annealing in this time.

Similar recovery measurements on the proton irradiated p-i-n diodes were consistent with the neutron damage results but yielded more detail than the neutron data because the temperature in the PS beam area was relatively stable (~27.5±0.5°C). Plotting the relative recovery against time (with the time on a log scale), as in fig.7, shows that the recovery of the leakage current damage following irradiation with $4x10^{14}$ protons/cm^2 has a uniform rate of annealing against log(time), ~10% per decade, which is independent of bias voltage. The slower drop at the start of the recovery period reflects the fact that some short-term annealing has already occurred during the 10 hour irradiation period. This overall annealing behaviour is consistent with the presence of a distribution of thermal energy barriers[7] that must be overcome in order for defects, such as vacancies and interstitials, to be annealed. Extrapolations based on these data therefore predict that ~10^4 hours are required for 50% recovery and 10^8 hours for a complete recovery (at this temperature) of the leakage current damage, assuming that all the leakage current damage recovers in this fashion.

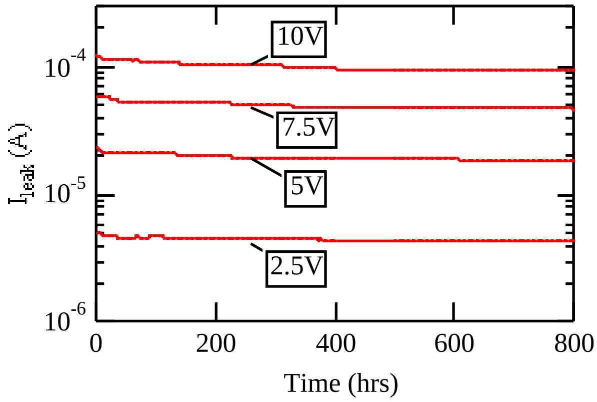

Fig. 6: Annealing of leakage current at different voltages in neutron damaged p-i-n diodes.

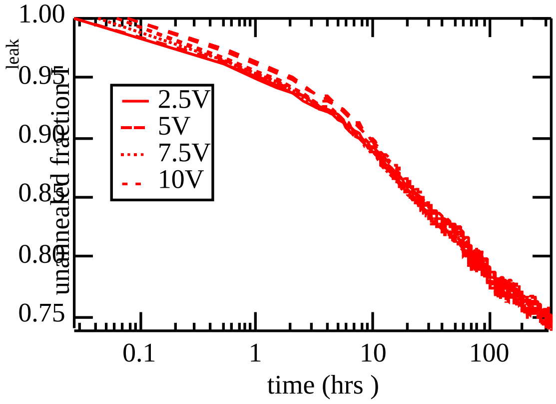

Fig. 7: Annealing of leakage current at different voltages with a logarithmic rate in proton damaged p-i-n diodes.

The observed recovery data is similar to that reported after 1MeV electron irradiation[7] using similar InGaAs p-i-n diodes (from the same manufacturer, but with different active area), where the recovery of leakage current was correlated with the annealing of the E2 defect in DLTS studies following irradiation[7]. This defect is an electron trap at E_C-0.29eV in the band-gap, i.e. very close to mid-gap as required for an efficient Shockley-Read-Hall generation-recombination centre. Measurements of the temperature dependence of the leakage current confirmed that the E2 defect was responsible for the leakage current[7]. Leakage current originating from generation centres in the band-gap is thermally activated, following the formula,

$$I \sim T^2 e^{-E_a / kT} \tag{1}$$

where the activation energy E_a equals the defect energy E_t, if one defect species is dominant. The temperature dependence of the leakage current was measured for several gamma and neutron irradiated p-i-n diodes at 1, 2, 5 and 10V reverse bias. The results obtained from gamma irradiated devices (after 100kGy) are shown in Fig. 8, yielding activation energies that were very similar to the results for electron damage[7] with E_a values between 0.46eV and 0.42eV depending on bias voltage (highest E_a for 2.5V bias, lowest for 10V). These E_a values are consistent with the E2 energy level.

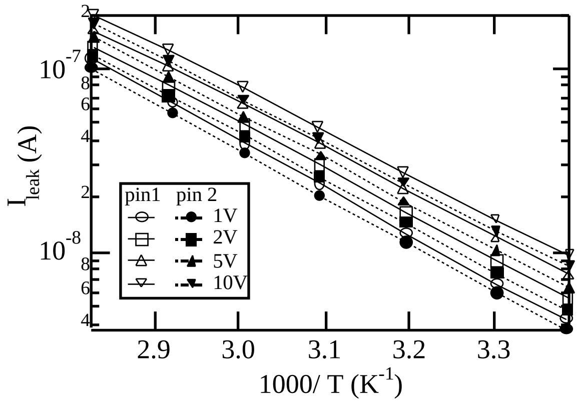

Fig. 8: Temperature dependence of leakage current in neutron damaged p-i-n diodes.
The p-i-n devices had both received a dose of 100kGy.

Results from three neutron damaged p-i-n diodes that had different fluences are shown in Fig.9. The current measured in all the devices was also thermally activated, with E_a~E(E2) when the current was less than 1µA at 300K. The value of E_a falls roughly linearly with increasing fluence (for a given voltage), as in Fig.10, in addition to a decrease in E_a for higher bias voltages. These results, at least for I_{leak}<1µA at 300K, are consistent with E2 defects also being responsible for the leakage current in neutron damaged devices, but with an additional component, possibly due to tunnelling[18], increasing the current at higher fluences and bias voltages.

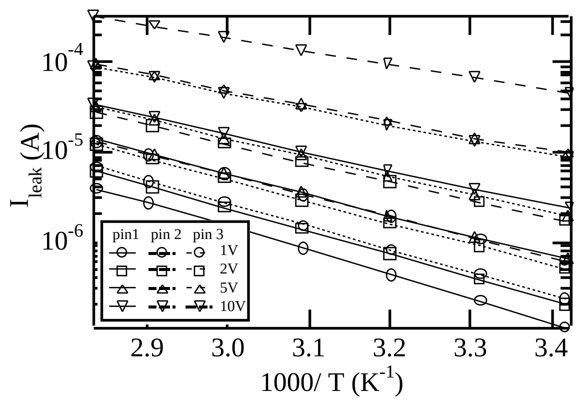

Fig. 9: Temperature dependence of leakage current in neutron damaged p-i-n diodes. The p-i-n devices had received the following fluences: pin1 1.5×10^{14}n/cm^2, pin2 4.0×10^{14}n/cm^2 and pin3 7.8×10^{14}n/cm^2.

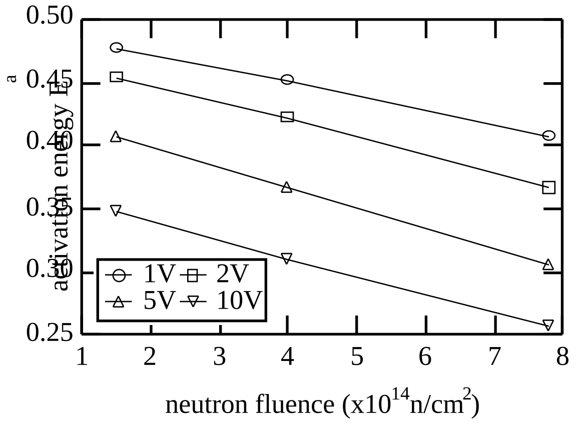

Fig. 10: Fluence and voltage dependence of thermal activation energy of leakage current.

3.2 Responsivity changes

The effect of neutron and proton irradiation on the p-i-n photocurrent is shown in fig.11. In general there is only a small decrease in response up to a certain fluence, around 2-4x10^{14}n/cm^2 or 2-6x10^{13}p/cm^2 depending upon the bias voltage. Above these fluences there is a rapid exponential drop in response. Data are illustrated for an input light level of 100µW, though similar results are obtained for other power levels (between 20µW and 200µW), when the device is under bias. With 0V bias the response falls faster with fluence for the higher power signals of 200µW. The larger density of electron-hole pairs due to the higher incident light power, in combination with the introduction of defect (trapping/recombination) centres into the active region, and the low field across the active region for 0V applied bias, is believed to be responsible for this effect.

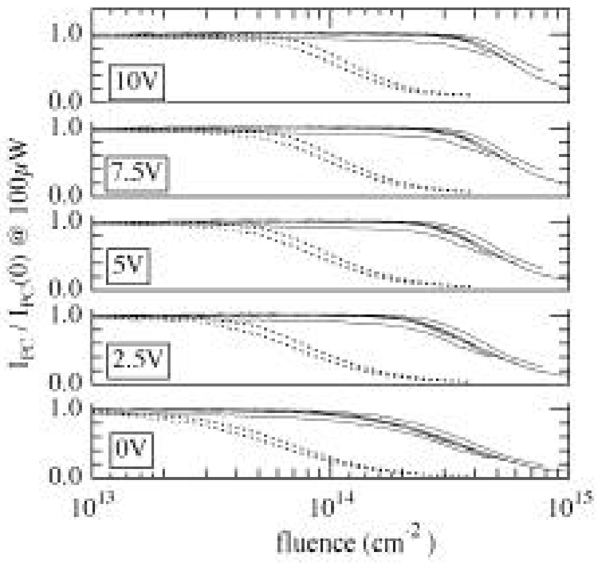

Fig. 11: Decrease in photocurrent I_{PC} for 100µW optical signal during neutron irradiation (solid lines) and proton irradiation (dashed lines) for bias voltages between 0V and 10V.

These p-i-n diodes will be used in digital data links, so a decrease in photocurrent may be acceptable if the ability to detect ON/OFF levels is retained by the system. The Bit Error Rate (BER) provides a good measure of this characteristic. BER measurements have been performed at 40Mb/s on an optical link using photodiodes irradiated to $6x10^{14}n/cm^2$ and 100kGy ^{60}Co gammas[19]. They show that it will be possible to maintain the BER below 10^{-12} after irradiation, and so maintain the ability to transmit data with these photodiodes.

Another estimate of the relative magnitude of proton and neutron damage can be determined by plotting the fluence at which the photocurrent (for example at 100μW incident optical power) has fallen by 50% as in fig 12. By comparison of the average values, for the different bias voltages, the 24GeV protons are observed to be ~5 times more damaging than the ~6MeV neutrons in terms of signal loss. There is also a linear increase with bias voltage in the fluence required to decrease the responsivity by 50%. This again illustrates that the magnitude of the applied field is important, after irradiation, in order maximise the collection of electrons and holes from the signal before they recombine at defect sites in the InGaAs layer.

No significant annealing of the damage to the responsivity was observed in either of the proton or neutron damage experiments. Fig.13 shows, for example, the recovery data from the proton damaged devices during the first 350 hours after irradiation, where the devices were kept at room temperature(~27°C), under 5V bias in the period between measurement cycles. The lack of recovery, compared to ~25% recovery of the leakage current during the same time interval(as in fig.7), would normally indicate that the same defects may not be responsible for both the leakage current and responsivity loss. However the responsivity appeared to be asymptotically approaching zero for the fluences above $2x10^{14}n/cm^2$ and $5x10^{13}p/cm^2$, whereas the leakage current was increasing at an ever growing rate with fluence. It is therefore unlikely that a fractional recovery of the leakage current would translate into a significant recovery of the responsivity, even if the same defects were responsible for the two different effects.

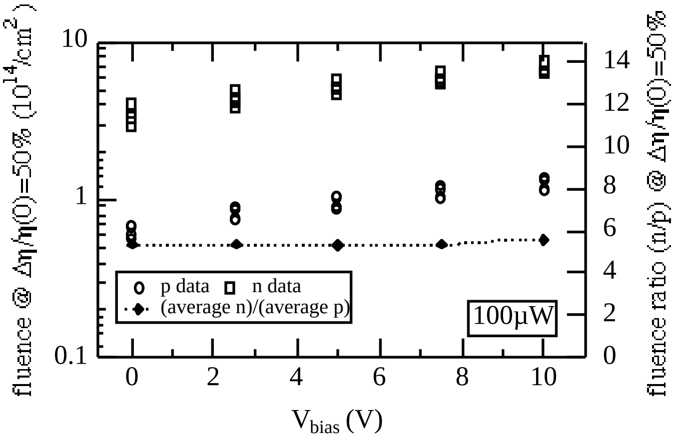

Fig. 12: Neutron and proton fluence required for response to fall to 50% of the initial value.

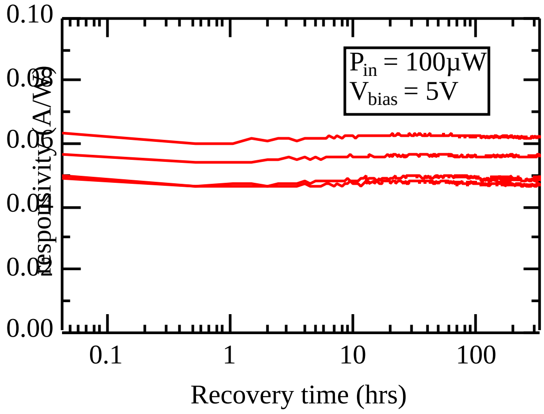

Fig. 13: Responsivity data for recovery period following proton irradiation

In terms of the effects of gamma irradiation to 100kGy, no significant damage to the device photocurrent was observed. An example of the data is shown in fig.14 for the photocurrent generated by 100µW signals (with 0V bias) during and after irradiation. Similar data was obtained for the measurements made under bias. The two devices with responsivity ~0.2A/W had been previously irradiated with neutrons to a fluence of $4x10^{14}n/cm^2$.

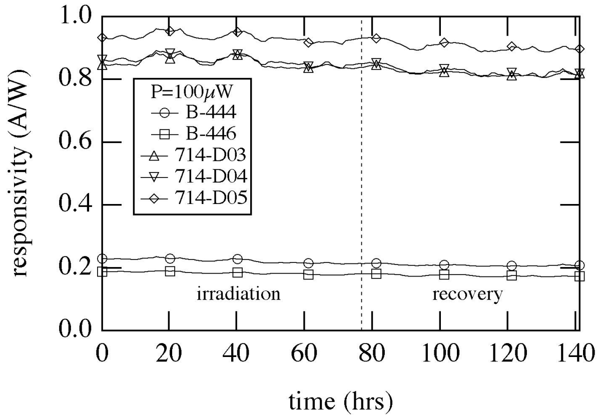

Fig. 14: Responsivity results during and after gamma irradiation.

4. Conclusions

Neutron and proton damage of InGaAs p-i-n diodes caused a large increase in leakage current, 6-7 orders of magnitude greater than the pre-irradiation values, after fluences of $10^{15}n/cm^2$ or $4x10^{14}p/cm^2$. In comparison gamma damage was much smaller with an increase of ~3 orders of magnitude after a dose of 100kGy. The leakage current anneals slowly with a log(time) dependence. Leakage current increases appear to be due to the build up of E2 defects[5-7] (at E_C-0.29eV in the band-gap) following from thermal activation measurements, with the activation energy decreasing at higher electric fields and fluences.

Proton and neutron damage affected the p-i-n responsivity whereas the gamma damage had no effect. For fluences up to $10^{13}p/cm^2$ and $10^{14}n/cm^2$ there was very little change in photocurrent(~10%) for a constant incident power, but for higher fluences the responsivity fell rapidly towards zero. No significant recovery of this damage was observed after irradiation.

In conclusion it would appear that the current prototype p-i-n photodiodes are sufficiently radiation hard for use in the CMS tracker, as BER can be maintained after irradation. More tests are planned with other samples from different manufacturers, which could show improved radiation resistance.

Acknowledgements

The authors wish to thank Bernard Cornet and Loic Baumard for assistance with the testing equipment. Marc Tavlet and Maurice Glaser of CERN, and Philippe Martin of ISN, are thanked for the dosimetry measurements.

References

[1] "Analogue Optical Links for the CMS Tracker Readout System", V. Arbet-Engels, G. Cervelli, K. Gill, R. Grabit, C. Mommaert, G. Stefanini and F. Vasey, presented at 7th Pisa Meeting on Advanced Detectors, to be published in Nucl. Instr. and Meth. A.

[2] "Effect of Neutron Irradiation of MQW Lasers to 10^{15}n/cm^{2}", K. Gill, V. Arbet-Engels, G. Cervelli, R. Grabit, C. Mommaert, G. Stefanini and F. Vasey, CMS Technical Note 1997/044.

[3] "Space-Radiation Effects on Optoelectronic Materials and Components for a 1300nm Fiber Optic Data Bus", P. W. Marshall et al., IEEE Trans. Nucl. Sci., Vol. 39, No. 6, p. 1982 (1992).

[4] "Radiation Effects in Optoelectronic Devices", H. Lischka et al., SPIE vol. 2425, p.43, (1994).

[5] "Radiation Effects in $Ga_{0.47}In_{0.53}As$ Devices", R. J. Walters, G. J. Shaw, G. P. Summers, E. A. Burke, S. R. Messenger, IEEE Trans. Nucl. Sci, Vol 39, No. 6, 2257 (1992).

[6] "Radiation-Induced Reverse Dark Currents in InGaAs Photodiodes", G. J. Shaw, S. R. Messenger, R. J. Walters and G. P. Summers, J. Appl. Phys. 73 (11), 7244 (1993).

[7] "Time Dependence of Radiation-Induced Generation Currents in Irradiated InGaAs Photodiodes", G. J. Shaw, R. J. Walters, S. R. Messenger and G. P. Summers, J. Appl. Phys. 74 (3), 1629 (1993).

[8] "Degradation and Recovery of $In_{0.53}Ga_{0.47}As$ Photodiodes by 1-MeV Fast Neutrons", H. Ohyama, J. Vanhellemont, Y. Takami, K. Hayama, T. Kudou, S. Kohiki and H. Sunaga, IEEE Trans. Nucl. Sci, Vol 43, No. 6, 3019 (1996).

[9] "Survivable Fiber Based Data Links for Satellite Radiation Environments", P. W. Marshall, C. J. Dale, E. J. Friebele, K. A. LaBel, SPIE CR50-paper 14 on Fiber Optics Reliability and Testing, 1993.

[10] The Compact Muon Solenoid Technical Proposal. CERN Report LHCC 94-38 (1994).

[11] "Uncertainties in Fluences and Doses at the CMS Inner Tracker", M.Huhtinen and C.Seez, CMS/TN 95-133 (Sept 1995).

[12] "Radiation Environment Simulations for the CMS Detector", M.Huhtinen, CMS/TN 95-198 (Dec 1995).

[13] "Studies of Neutron Moderator Configurations around the CMS Inner Tracker and ECAL", M.Huhtinen, CMS/TN 96-057 (June 1996).

[14] "Reliability of InGaAs Detectors and Arrays", A. M. Joshi, G. H. Olsen and S. R. Patil, Proc. SPIE 1580, 34 (1991).

[15] J. Gower, "Optical Communication Systems", Prentice Hall, New York, 1993.

[16] P. Nugent and co-workers of Italtel, 20019 Settimo Milanese, Italy measured p-i-n leakage, capacitance and responsivity on fully packaged and pigtailed photodiodes prior to shipping.

[17] "A neutron irradiation facility featuring cryogenic temperatures and dedicated to Large Hadron Collider detector design", J. Collot et al., Nucl. Inst. and Meth., A 350 (1994), p525.

[18] J. Bourgoin and M. Lannoo, "Point Defects in Semiconductors II", Springer-Verlag Berlin Heidelbeg New York, 1983, pp. 199.

[19] "Characterization of Optical Data Links for the CMS Experiment", V.Arbet-Engels, G.Cervelli, K.Gill, R.Grabit, C.Mommaert, G.Stefanini, and F.Vasey, Proceedings of the Third Workshop on Electronics for LHC Experiments, CERN/LHCC/97-60, 21 October 1997, p287