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Pion radiation damage in InGaAs p-i-n photodiodes

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Abstract

Fully packaged InGaAs p-i-n photodiodes for use in CMS Tracker optical digital timing and control links have been irradiated at room temperature with 330MeV positive pions. Measurements of the leakage current and photocurrent response were made in-situ for pion fluences up to $3.9 \times 10^{14} \pi^+/cm^2$. The leakage current increases from <1nA to 40µA at 5V reverse bias and the photocurrent for 100µW incident optical power decreases from 90µW to 18µW after $2 \times 10^{14}\ \pi^+/cm^2$. 330MeV pions cause a similar level of damage to 24GeV protons and several times more damage than 6MeV neutrons. The leakage current damage anneals slowly and no significant recovery of the photocurrent damage occurs at temperatures up to 80°C. Although the damage effects are relatively large they are tolerable in the CMS tracker digital timing/control optical link system.

1. Introduction

A digital optical link is being developed at CERN for distribution of timing, trigger and control signals in the CMS tracker[1]. InGaAs p-i-n photodiodes will be used at the front-end to receive the 40MHz signals generated by 1310nm lasers in the counting room. The photodiodes in the tracker will be subjected to high radiation fluences. For example, at a radius of 20cm from the beam axis in the barrel the particle fluences[2] are expected to be ~10^{14}(1MeV neutrons)/cm^2, ~1.6×10^{14} charged hadrons/cm^2 (80% pions, 10% protons, 10% kaons with energies in the range of several hundred MeV), plus a total ionising dose of ~100kGy, for an integrated luminosity of $10^5 pb^{-1}$.

InGaAs photodiodes are well suited to IR wavelength optical links, with very low leakage currents (~10pA @ -5V) and high responsivity, typically ~0.8-0.9A/W at 1310nm. This wavelength is a standard for modern telecommunications and many manufacturers offer products in a variety of compact packages. A thorough study of a wide range of receivers is in progress and several candidate devices have been identified. Epitaxx[a] back-illuminated p-i-n photodiodes have been the most widely studied. The devices are supplied by Italtel[b] in a prototype 8-pin mini-DIL package, common to both lasers and p-i-n's used in the tracker 1-way analogue and digital prototype optical links. Measurements of neutron, gamma and proton damage on Italtel/Epitaxx p-i-n photodiodes have already been carried out[3,4] and to complete this series of irradiation studies, we have irradiated the same type of p-i-n photodiodes with 330MeV (positive) pions at the Paul Scherrer Institute (PSI).

Our previous results[3,4] show that bulk (displacement) damage is more important than ionisation damage for the fluences and dose levels relevant to the CMS Tracker. Bulk damage arises when host atoms are displaced from their crystal lattice positions by incident energetic particles. If sufficient recoil energy is generated, for example by a fast incident hadron, many more atoms can be subsequently delocalised in a 'displacement cascade' creating dense clusters of vacancy-interstitial (V-I) defects. Although many of the initial V-I pairs recombine immediately, some will escape recombination and form stable defects, or will diffuse away until reaching a surface or combining with other defects or impurities producing defect complexes.

Radiation induced defects can introduce generation-recombination centres into the active volume of a semiconductor device[5]. In p-i-n photodiodes, this generally causes an increase in the leakage (or dark) current[6,7] and a loss of signal due to trapping/recombination of signal charge carriers[8]. A radiation induced defect has been identified close to the centre of the band-gap[6,7] which may be responsible for the observed effects in irradiated InGaAs p-i-n diodes. Interpretation of the data is generally complicated due to the different p-i-n (and InP substrate) stuctures, geometries and doping levels, which vary from manufacturer to manufacturer. In this report a comparison will be made between the damage from pions to that from neutrons, protons and gammas in identical devices in terms of the increase in leakage current and decrease in photocurrent.

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[a] Epitaxx Corporation, 7, Graphics Drive, West Trenton, NJ 08628, USA.
[b] Italtel, Photonic Component Unit, Castelletto, 20019 Settimi Milanese (MI), Italy.

2. Experiment

2.1 Devices

Five Epitaxx p-i-n photodiodes, packaged and supplied by Italtel, were irradiated with pions in this experiment. The devices are labelled 1 to 5 in the following sections. Details of the device structure and packaging have been reported previously[3] and are only summarised here. The p-i-n structure consists of an 75μm diameter epitaxially grown InGaAs active layer (~3μm thickness) grown on an InP substrate. The die is soldered onto a planar silicon optical submount, which is then epoxy glued into in a compact 8-pin mini-DIL (dual-in-line) package. Optical connection is made via a 2m long, pure-silica core (PSC), single-mode fibre pigtail aligned with the detector using an etched, reflective V-groove in the silicon submount beneath the detector. The input end of the fibre pigtail is terminated with a standard FC/PC optical connector.

2.2 Irradiation set-up and dosimetry

The pion beam characteristics and dosimetry measurements are given in an accompanying CMS Note[9] on lasers which were irradiated at the same time as the p-i-n photodiodes. A single momentum value of 300MeV/c (330MeV energy) was used in order to obtain a sufficiently high fluence in the time available. Samples to be irradiated were arranged, along with aluminium dosimetry foils, in stack along the beam axis. The devices were irradiated for 96 hours at room temperature and the fluences received were 3.9, 3.4, 3.3, 2.9 and $2.8\text{x}10^{14}\pi/\text{cm}^2$ (±10%) for devices 1-5 respectively.

2.3 In-situ measurements

During the irradiation and recovery period p-i-n leakage current and photocurrent response were measured at periodic intervals: 30 minutes at the start of the test and later 1 hour towards the end of the annealing period. The device characteristics were measured for several different reverse bias voltages: 0, 2.5, 5, 7.5 and 10V. In between measurement cycles, which typically took 5 minutes, the p-i-n diodes were all biased at 5V reverse bias without illumination.

The leakage current was measured by monitoring the device current without illumination (via the voltage across a 1kΩ series resistor), then subtracting the offset value measured at 0V (due to an offset in the DMM used in the data-logger). The photodiodes were illuminated for photocurrent measurements by an external laser, optically connected to the p-i-n diodes via an 8-way splitter. The photocurrent was measured for optical power levels between 0 and 500μW by monitoring the p-i-n current whilst ramping the drive current to the external laser. Each data point is the average of 3 values measured after a settling time of 1s so the photocurrent data is essentially for dc optical power levels. One channel of the splitter was connected to an external p-i-n diode which was used to monitor any fluctuations in the laser power output, for example due to a threshold shift resulting from a change in the ambient temperature. The corresponding data for the p-i-n photocurrents could then be normalised to a nominal laser power level, assuming that the insertion losses at the splitter and patch cord connections remained constant.

The temperature in the beam area was also measured, but not controlled, and values between 18°C and 20°C were measured in the beam area during irradiation (and between 16°C and 22°C during annealing). The temperature in the control room, where the external laser was situated, was a relatively stable value of 21.2(±.3)°C. After the irradiation step was completed, the p-i-n diodes were removed from the beam and stored for one month in the beam area under the same bias and measurement conditions with no modifications to the optical connections. Further measurements of the damage annealing were later continued at CERN using different temperatures between 40 and 80°C.

3. Results

3.1 Radiation damage effects

The pre-irradiation leakage currents were below the sensitivity of the measurement system used during the test which was limited to ~1nA by the dynamic range of the datalogger. Data sheets provided by the supplier indicated pre-irradiation leakage currents at 5V reverse bias of ~10pA. The initial responsivity of the p-i-n diodes was ~0.9A/W. Fig. 1 illustrates the effect of pion damage on the p-i-n characteristics (for p-i-n 1), showing a large increase in leakage current and a drop in responsivity.

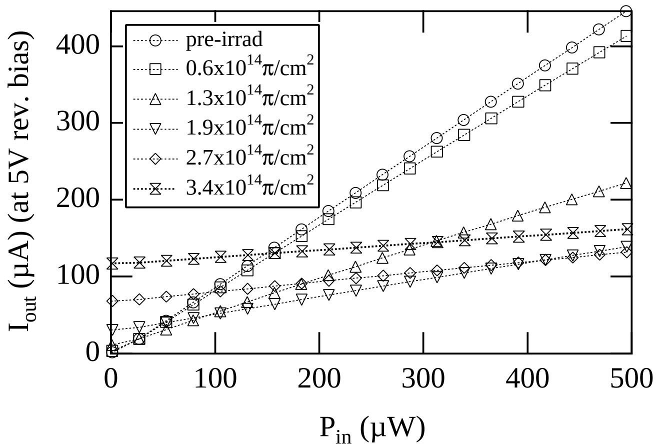

Fig. 1: Degradation of the p-i-n characteristics due to 330MeV pion damage (data for p-i-n 1)

Fig. 2 shows the leakage currents measured in all five devices as a function of pion fluence. Fig. 3 illustrates the pion damage to the device responsivity in terms of the photocurrent for a 100μW 1310nm incident optical signal (normalised to the pre-irradiation value). The damage effects in the p-i-n photodiodes are consistent with the build-up of radiation induced defects in the bulk leading to the generation of dark current and the trapping/recombination of signal charge.

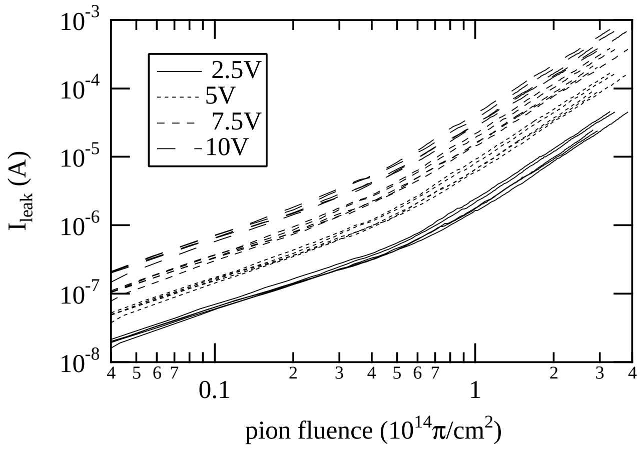

Fig. 2: Leakage currents as a function of pion fluence at different reverse bias voltages: (a) 2.5V, (b) 5V, (c) 7.5V and (d) 10V.

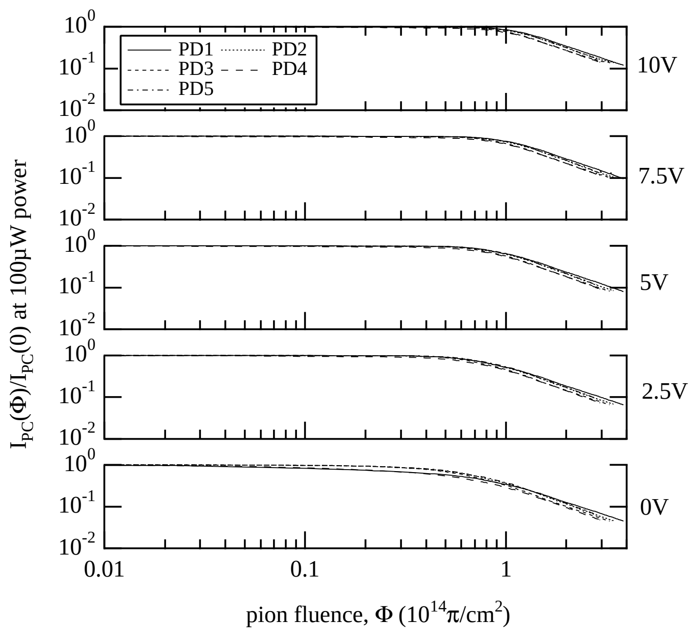

Fig. 3: Photocurrent degradation in pion irradiated p-i-n photodiodes. The values are normalised to the initial, pre-irradiation signal for an optical power level of 100μW.

It should be emphasized that the sharp decrease in photocurrent response that occurs after ~$5x10^{13}\pi/cm^2$ is specific to this type of device. In our recent neutron damage studies, using both front-illuminated and back-illuminated Epitaxx InGaAs p-i-n photodiodes of identical geometry, the responsivity of the front-illuminated devices remained high (~80% of the initial value) up to the tested fluence of $10^{15}n/cm^2$ whereas a sharp decrease in the photocurrent was measured in the back-illuminated devices after $3x10^{14}n/cm^2$.

The reason for this difference in the radiation hardness between front- and back-illuminated devices is currently being investigated, but the effects may be due, for example, to a build-up of predominantly acceptor-type defects in the bulk. This would eventually lead to ‘type-inversion’ of the nominally intrinsic (but actually lightly-doped n-type) InGaAs layer from n-type to p-type. Type-inversion of the InGaAs layer after ~$5x10^{13}\pi/cm^2$ would explain the sharp change in the response at this fluence, as uncompensated negatively charged acceptors in the InGaAs layer would be effective trapping centers for signal induced holes after type-inversion. Due to the short optical absorption length of InGaAs at 1.3µm, this would be more damaging in back-illuminated p-i-n diodes than in front-illuminated devices because signal induced holes must travel a greater distance through the InGaAs layer in back-illuminated diodes.

In terms of the digital link operation inside the CMS tracker, the radiation induced leakage currents may approach the amplitude of the optically-induced signals in the digital links (~100µA before radiation-induced attenuation). The link receiver electronics therefore have to compensate for leakage currents up to ~100µA. For the responsivity loss, even though the damage effect is apparently very large for these devices, we have demonstrated[1] a bit-error-rate $<10^{-12}$ in a 40Mb/s digital link using a neutron damaged p-i-n diode of the same type (with 70% responsivity loss).

3.2 Annealing of the damage

3.2.1 Room temperature

Measurements of the leakage current and photocurrent continued for 610 hours following irradiation. The devices were stored in the irradiation area (but outside the beam) at room temperature, biased at -5V with measurements made under the same conditions as during irradiation. Fig. 4(a) shows the annealing of the leakage current damage during that time, in terms of the unnealed fraction of the damage (the leakage current divided by the value measured at the end of the irradiation step). Around 16% of the leakage current damage annealed. In contrast, no significant recovery of the photocurrent damage occurred, as illustrated in Fig. 4(b).

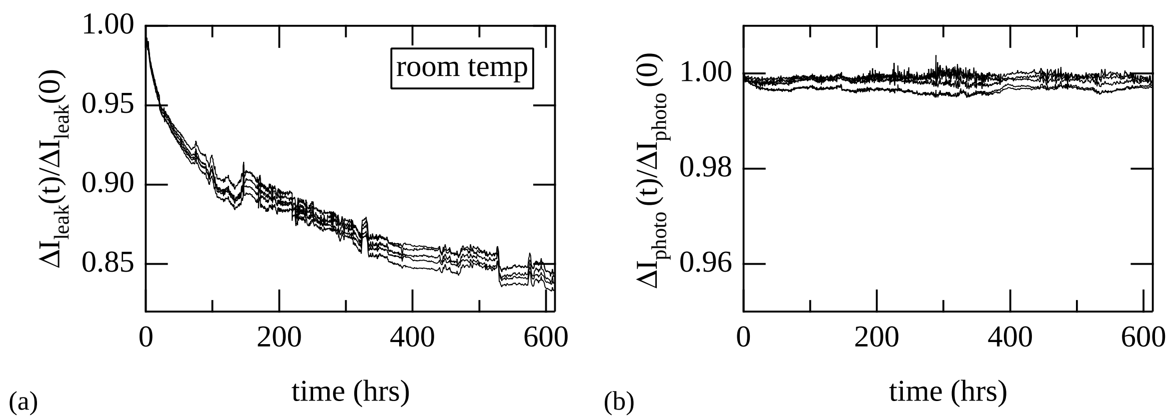

Fig. 4: Room temperature annealing of (a) leakage current and (b) photocurrent damage following irradiation. The plot shows the unannealed fraction, i.e. the fraction of damage remaining relative to the damage at the end of irradiation.

3.2.2 Higher temperature steps

The annealing measurements were continued (after a ~2000 hour interval) at CERN, using an oven to accelerate the recovery effects. The devices were stored (under the same bias/illumination conditions as for the irradiation test) for consecutive 260 hour steps at 40°C, 60°C and 80°C. The annealing of the leakage current is shown in Fig. 5 where 42-46% of the damage was recovered by the end of the 80°C step. In contrast, only ~1% of the damage to the photocurrent annealed during these stages.

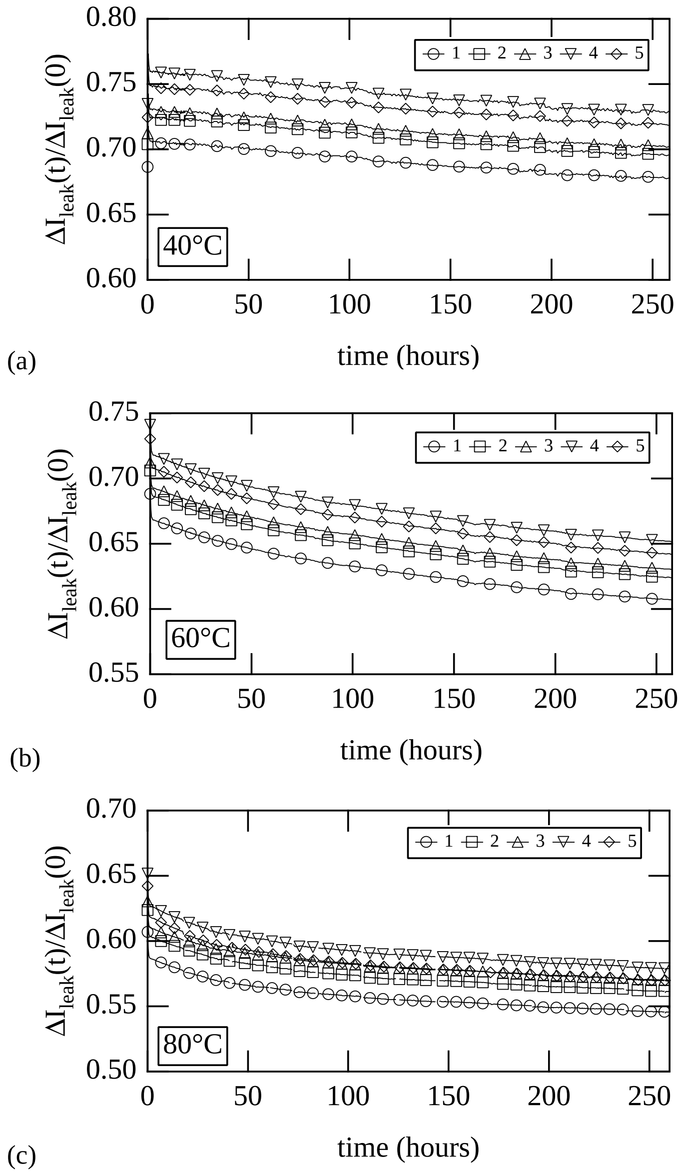

Fig. 5: Annealing of leakage current damage during consecutive 260 hr temperature steps of (a) 40°C, (b) 60°C and (c) 80°C.

4. Comparison of damage in pion, neutron and proton tests

P-i-n diodes of the same type have now been irradiated under similar conditions (-5V bias at room temperature) with pion, neutron, proton and gamma sources. The overall effects of leakage current increase and responsivity loss are qualitatively similar for pions, neutrons and protons. Damage resulting from ^{60}Co gamma irradiation was negligible in comparison, with ~10nA leakage current (at -5V bias) and no signal loss after 100kGy[4] so gamma damage will not be discussed further.

The pion and neutron damage data can be compared directly as the exposures were of the same duration, 96 hours. The proton irradiation was over only 10.5 hours and the proton damage data should be corrected for annealing to compare with results obtained in an exposure of 96 hours. However, due to the non-linear dependence of damage on fluence, it is not possible to extrapolate precisely the proton damage to a longer exposure time and a direct comparison has to be made for a given fluence. Since only 20% of the proton induced leakage current damage annealed in 96 hours after the 10.5hr irradiation[3] the systematic error in the pion to proton comparison will remain relatively small (~10% over-estimate of the proton induced leakage current damage over a 96hr irradiation step).

For the photocurrent measurements, no corrections are necessary for the different exposure times since the damage to the responsivity is essentially permanent with no significant annealing of the damage at room temperature (or higher temperatures) following the pion, proton and neutron irradiation tests.

The radiation damage resulting from 330MeV pions is compared to that from 6MeV neutrons and 24GeV protons in Figs. 6 and 7 for the leakage current and photocurrent respectively. Five devices were irradiated with neutrons and four with protons, all under 5V reverse bias and illumination conditions identical to the pion test. Due to the non-linearity of the effects with fluence, comparisons have to be made in terms of the fluence required to produce a certain level of damage, as opposed to a comparison of damage increase per unit fluence. 330MeV pions are similar to 24GeV protons for both leakage and photocurrent damage. The pions and protons are about 10 times more damaging than 6MeV neutrons in terms of leakage current and around 4-5 times greater in terms of photocurrent damage.

It is interesting to note that the large difference observed between the effects of 6MeV neutrons and those due to 24GeV proton and 330MeV/c pions is qualitatively similar to that observed in irradiated GaAs detectors, where the ratio is 1:3.1:3.8 for 1MeV neutrons, 24GeV protons and 330MeV pions respectively[10]. In contrast, the damage ratios are all very similar in silicon detectors irradiated with the same three radiation sources (n:p:π = 1:0.93:0.93)[11]. The explanation for this difference in damage ratios between Si and GaAs is related to the masses of the constituent elements and the fraction of the kinetic energy of recoiling atoms/nuclei that is dissipated in further atomic displacement, i.e. the non-ionizing energy loss (NIEL)[12]. The NIEL fraction of the recoil energy is larger for heavier atoms for a given recoil energy. The three types of source have similar NIEL values for silicon but 330MeV pions and 24GeV protons are both expected to have NIEL values several times greater than 1MeV neutrons. The differences we observe for the damage to p-i-n photodiodes between pion, proton and neutron damage are therefore qualitatively consistent with the NIEL hypothesis though detailed calculations have yet to be performed.

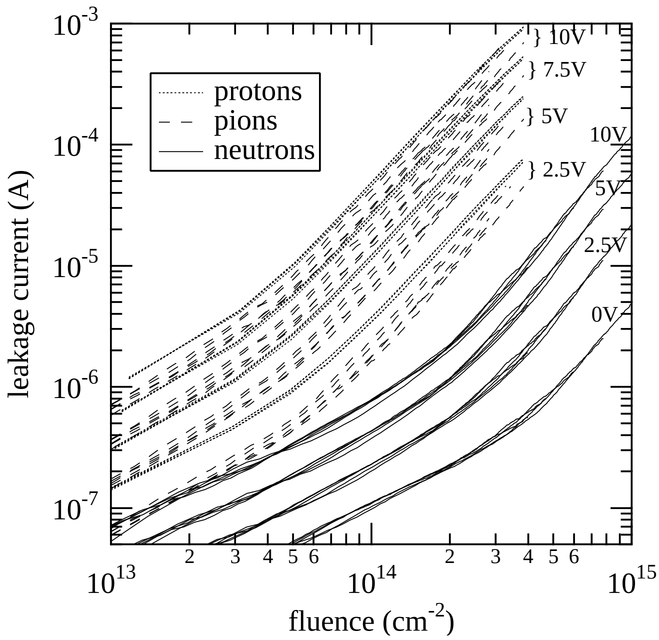

Fig. 6: Comparison of leakage current damage in p-i-n photodiodes due to 330MeV pion, 6MeV neutron and 24GeV proton irradiation. Pre-irradiation values were ~10pA at -5V.

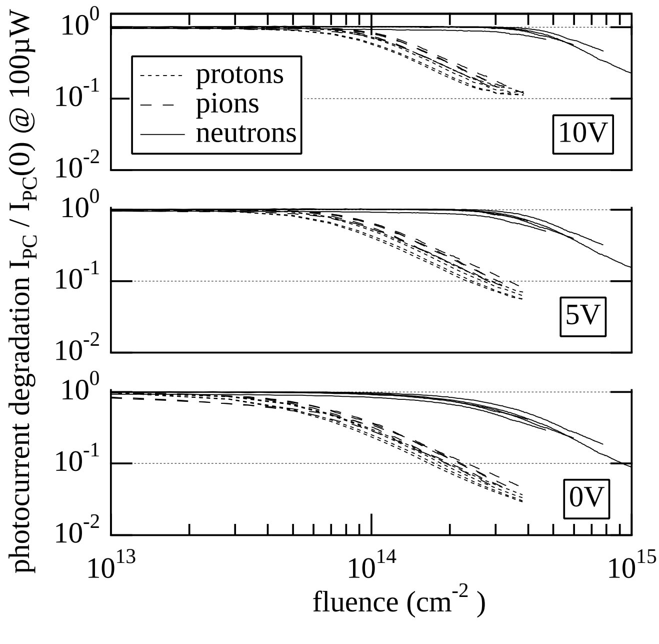

Fig. 7: Comparison of photocurrent degradation in p-i-n photodiodes irradiated with 330MeV pions, 6MeV neutrons and 24GeV protons. The photocurrent is shown for 100µW optical power, with the data normalized to the pre-irradiation signal level (~90µA).

5. Conclusion

In the innermost parts of the CMS tracker the radiation flux will be dominated by pions with ~300MeV energy. We have measured the radiation damage effects due to 330MeV pions (π^+) on prototype p-i-n photodiodes for use in the tracker digital control/timing links. Five photodiodes mounted in mini-DIL packages were irradiated at room temperature with pion fluences between 2.8 and $3.8 \times 10^{14} \pi/cm^2$. The pion damage effects are summarized in Table 1 for a fluence of $2 \times 10^{14} \pi/cm^2$, which is typical of 10 years of operation at 20cm radius from the LHC beam axis. This essentially represents a worst-case as most of the links will be located at greater radial distances from the beam interaction point and will therefore be exposed to much lower particle fluences. Further tests are planned to accurately determine the annealing rates as a function of temperature, as the innermost (silicon) part of the CMS tracker will be maintained at -10°C and the outer layers of (gas microstrip) tracking detectors will be operated at 20°C.

	pre-irradiation	after $2 \times 10^{14} \pi/cm^2$
p-i-n leakage (@ 5V)	<0.5nA	40μA
p-i-n photocurrent (@ 5V, 100μW)	90μA	18μA

Table 1: Summary of average amounts of 330MeV pion damage after $2 \times 10^{14} \pi/cm^2$ in InGaAs p-i-n photodiodes

The damage effects are most likely due to displacement damage in the active region leading to enhanced generation-recombination at defect states in the band-gap. There is more damage from the pions (and protons) relative to the neutrons, which is in contrast to the similar relative damage levels observed in irradiated silicon devices. For the p-i-n photodiodes, 330MeV pions caused a similar amount of damage as 24GeV protons and were several times more damaging then 6MeV neutrons, with the precise factor dependent upon the amount of damage being compared. The large difference in the damage factor between 330 MeV pions (and 24GeV protons) relative to 6MeV neutrons is consistent with NIEL arguments and a more detailed model is being developed to calculate the NIEL in the p-i-n diodes. In addition, a further high energy proton test is planned to measure the effect of incident particle direction on the radiation damage.

In terms of operating the digital control and timing distribution links, where p-i-n diodes will be situated in the tracker volume, the increases in leakage current will be compensated by the receiver electronics, and the loss of response will not significantly affect the bit-error-rate at 40Mb/s. The photocurrent degradation in the p-i-n photodiodes is specific to this type of back-illuminated device and, in our other recent tests, front-illuminated photodiodes have been found to be more radiation-hard.

Acknowledgements

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References

[1] F. Vasey et al, Proceedings of IEEE Nuclear Science Symposium, 1997, to be published in IEEE Trans. Nucl. Sci., June 98.

[2] CMS Tracker Technical Design Report (1998). Note that uncertainties in the fluence values may be at the level of 50%.

[3] K. Gill et al., Proceedings of Radiations and their Effects on Devices and Systems Conference (RADECS) 1997.

[4] J. Troska et al, CMS Technical Note 1997/102.

[5] J. E. Gover and J. R. Srour., "Basic Radiation Effects in Nuclear Power Electronics Technology", Sandia Laboratory Report, SAND85-0776 (1985).

[6] G. Shaw et al., J. App. Phys. Vol. 73, p.7244, 1993.

[7] R. J. Walters et al., IEEE Trans. Nucl. Sci, Vol 39, No. 6, p.2257, 1992.

[8] H. Ohyama et al., IEEE Trans. Nucl. Sci. Vol. 43, No. 6, p.3019, 1996.

[9] K. Gill et al, CMS Technical Note 1998/046.

[10] A. Chilingarov et al., Nucl. Instr. and Meth. A.395, p.35, 1997.

[11] S. J. Bates et al., Nucl. Instr. and Meth. A.379, p.116, 1996.

[12] G. P. Summers et al., IEEE Trans. Nucl. Sci., vol.35, p.1221, 1988.