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Radiation tests of photodiodes for the ATLAS SCT and PIXEL opto-links

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Abstract

In previous research, epitaxial Si PIN photodiodes produced by Centronic which will be used in the ATLAS semiconductor tracker have been irradiated with 1 MeV neutrons and 24 GeV protons with fluences up to an equivalent of 10^{15} 1 MeV neutrons [1,2]. In this work 30 MeV proton beams were used to irradiate Centronic and Truelight epitaxial Si PIN diodes with accumulated fluences of up to 2.1×10^{14}–30 MeV p cm^{-2}, an equivalent of 5.7×10^{14} cm^{-2} 1 MeV neutrons, to reach the pixel radiation environment. The responsivity was measured with different levels of fluence in order to study the responsivity behaviour of two different types of photodiodes. The responsivity behaviour of these two photodiodes was similar: a linear degradation at large fluences, $>10^{14}$ 30 MeV p cm^{-2}, but with different slopes. The response of the Centronic PIN diode showed a degradation to 73% after a proton fluence of 10^{13} p cm^{-2} of 30 MeV and a linear degradation at a rate of -0.32% per 10^{13} p cm^{-2} for fluences larger than 10^{13} 30 MeV p cm^{-2}. The Truelight PIN degraded to 84% after a fluence of 10^{13} p cm^{-2}, with a linear degradation rate of –1.8% per 10^{13} p cm^{-2}. Annealing of both photodiodes with a bias voltage of –10 V for 180 h showed a 7% recovery for the Truelight PIN diode and a 2% recovery for the Centronic PIN diode after irradiation fluences of 2.1×10^{14} p cm^{-2}. A gamma source was also used to irradiate 6 Truelight PIN diodes with a total dose larger than 600 kGy; no obvious responsivity change was observed in this case.

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Keywords: Epitaxial Si photodiodes; 30 MeV protons irradiation; Responsivity; ATLAS semiconductor; ATLAS pixel detector; LHC

1. Introduction

Optical links will be used in the ATLAS semiconductor tracker (SCT) at the large hadron collider (LHC). There will be 8176 vertical cavity surface emitting lasers (VCSELs) and 4088

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photodiodes in the SCT. In the ATLAS SCT the predicted fluences over a ten-year operating life are $\sim 2 \times 10^{14}$ neutrons cm^{-2} and $\sim 1.5 \times 10^{14}$ charged-hadrons cm^{-2}. The predicted ionizing dose is ~100 kGy for silicon (Si) devices. The opto-packages that will be used in the binary readout data link are shown in Fig. 1.

The opto-package contains two VCSELs, used to transmit data from the silicon strip detector modules to the off-detector electronics, and one PIN photodiode, used to distribute the timing, trigger and control (TTC) data from the counting room to the front-end electronics [3]. The opto-packages are custom designed by Academia Sinica, Taiwan and manufactured by Radaintech, Taiwan. The opto-package is specifically designed to have low mass and to be non-magnetic and radiation hard to match the SCT requirements. Truelight VCSELs, Centronic PIN diodes and Fujikura fibres will be used in this opto-package for the SCT link. The results of the radiation hardness studies of these PIN photodiodes, VCSELs and Fujikura fibres have been described in previous publications [1,2,4,5]. The Truelight PIN diode has also been used in our prototype opto-packages. Its initial responsivity has typically been 0.55 A/W, greater than the Centronic PIN, which has typically been 0.45 A/W.

Similar multi terminal (MT) receptacle array opto-packages [6] have been proposed for use in the read-out of data from the pixel detector [3] which requires a further 2500 photodiodes operated at a fluence and dose rate of up to 2.5×10^{14} 1 MeV neutrons per cm^2 and 500 kGy for Si devices. The Truelight VCSEL is extremely radiation hard and would, therefore, be suitable for use in the pixel detector. In this report we present the measurement of the responsivity performance of both the Truelight and Centronic Si PIN diode after irradiation with 30 MeV proton beams up to fluences of 2.1×10^{14} p cm^{-2} equivalent to 5.7×10^{14} cm^{-2} 1 MeV neutrons. Also 6 Truelight PIN diodes were irradiated with doses of 600 kGy from a gamma source which is the pixel radiation environment.

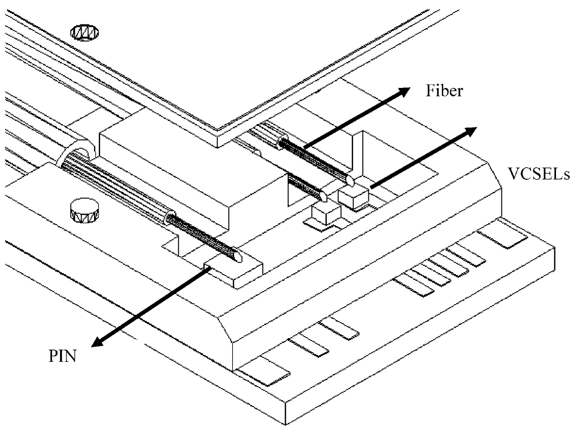

Fig. 1. Schematic diagram of the SCT opto-package.

An overview of these two photodiodes, with radiation damage, is given in Section 2. The expected radiation environment is defined in Section 3. The experimental set-up and radiation sources used are described in Section 4. The results of the radiation hardness studies are discussed in Section 5 and finally some conclusions are drawn in Section 6.

2. Photodiodes and radiation damage theory

The epitaxial silicon PIN photodiodes are made from an n-type substrate, which has a low doped background (intrinsic) n-type layer, followed by a p-type layer grown epitaxially on top [2]. The simple specs of both the Centronic[1] PIN diode and the Truelight[2] PIN diode are available on their web pages [7]. The responsivity of the Truelight PIN diode was measured to about 0.6 A/W in this test before irradiation and the Centronic PIN diode was measured to about 0.5 A/W, consistent with [1]. Both PIN diodes are suitable for use, in SCT and pixel applications, before irradiation.

The degradation of the response is probably related to a change, from n-type to p-type, of the low-doped layer as a result of the incident radiation forming acceptor levels, known as type inversion of these substrate devices [8]. At low integrated fluences, $\phi < 10^{13}$ 30 MeV p cm^{-2}, the acceptor states compensate the donor states until

[1]Centronic, UK, AEPX-10.

[2]Truelight, Taiwan, TPD-8D12.

the effective doping concentration N_{eff} is reduced to that of the intrinsic silicon. On the other hand, at higher fluences, the effective doping is mainly provided by the radiation-induced defects, so that N_{eff} may be parameterized as [2,8]

$$|N_{\mathrm{eff}}| \sim \beta\phi, \tag{1}$$

where β is a factor related to the rate of creation of an acceptors state per unit path length in silicon.

We can model the normalized responsivity (R_{N}) change at the higher fluences, larger than the critical fluences, $\phi > \phi_{\mathrm{c}} = 10^{13}$ 30 MeV p cm^{-2} observed in this work, in the linear equation below:

$$R_{\mathrm{N}} = 1 - \beta_{\mathrm{N}}\phi/\phi_{\mathrm{c}} - R_{\mathrm{c}}, \tag{2}$$

where β_{N} and R_{c} are linear parameters related to the decay rate. The responsivity decrease dramatically at the beginning (R_{c}) is due to the donor state compensation.

3. Expected radiation environment

A mixture of high-energy charged particles, low energy neutrons and photons will be produced in the proton–proton collisions at LHC, leading to possible radiation damage of detector elements and electronics. All parts of the detector, including the opto-links, will be affected by the radiation damage. The effect of displacement damage in semiconductor devices has been found to scale with the total non-ionizing energy loss (NIEL) [9,10].

The expected spectra of charged and neutral particles in the ATLAS inner detector were simulated using the FLUKA transport code. The standard ATLAS luminosity scenario of 3 years of low luminosity (10^{33} cm^{-2} s^{-1}) followed by 7 years of high luminosity (10^{34} cm^{-2} s^{-1}) operation was assumed. It was convenient to convert the fluences into the equivalent fluences of 1 MeV neutrons by assuming the NIEL scaling hypothesis. This was done by integrating the differential spectrum weighted by the ratio of NIEL for a particle of energy E and a 1 MeV neutron.

$$F_{\mathrm{neq}} = \int \frac{\mathrm{d}N}{\mathrm{d}E} \frac{\mathrm{NIEL}(E)}{\mathrm{NIEL}(n_{1\,\mathrm{MeV}})}\, \mathrm{d}E. \tag{3}$$

Table 1
Expected NIEL values for Si and fluences for the inner SCT and PP0 for 10 years of LHC operation [9,10]

Particle type	Energy (MeV)	SCT layer fluences (10^{14} cm^{-2})	PP0 layer fluences (10^{14} cm^{-2})
N	1	0.73–1.1[a]	2.5–3.7[a]
P	30	0.3–0.42[a]	0.9–1.4[a]

[a]The worst case with safety factor 1.5.

The NIEL values for Si used were taken from Refs. [9,10]. A safety factor of 1.5 was applied to take into account all the uncertainties in the calculations [3]. The resulting fluences for the inner layer of the SCT and the patch panel PP0 and the position for the pixel opto-links, which will receive the fluences, are given in Table 1, showing different particle types and energies.

The expected ionizing radiation dose for the inner layer of the SCT and pixel, during the 10 years of ATLAS operation, is 100 and 500 kGy, respectively [3].

4. Experimental set-up and irradiation facilities

4.1. 30 MeV protons

Beams of protons with a kinetic energy of 30 MeV were used from the TR-30 Cyclotron Facility of the Institute of Nuclear Energy Research (INER) in Taiwan. The beam currents used were about 10 nA. An external beam line was used and the beam was collimated and allowed to pass through a thin window. The beam spot size was 1 cm in radius at the exit window. A 5 mm × 10 mm square window with 7 mm thick Al walls was placed between the beam exit window and the target to secure the irradiation area. The target was placed about 20 cm downstream and the typical flux was about 2×10^{10} cm^{-2} s^{-1}. A step motor, controlled by a notebook placed outside the radiation room, was used to adjust the exposed window position, which was monitored by a CCD camera in the radiation room.

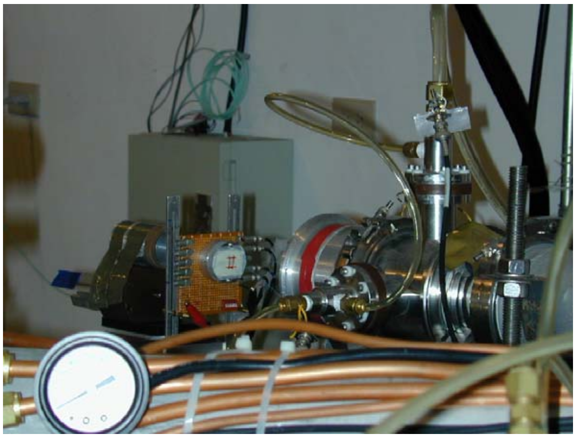

Fig. 2. Faraday cup and irradiation window in the external proton beam line.

A Faraday cup was placed behind the target to collect the charge. The current signal was sent to a digital current integrator [3] and the resulting digital signal was then measured.[4] A typical current, 1.5 nA, was measured at the Faraday cup, which was consistent to the beam flux setting. The total fluences accumulated were $2.1\times10^{14}\,\mathrm{p\,cm^{-2}}$ to reach the PP0 radiation environment. A photograph of the target and the beam line is shown in Fig. 2.

4.1.1. PIN photodiode responsivity measurements

Four Truelight PIN diodes and one Centronic PIN diode were wire bonded to one carrier PCB. These PIN diodes were coupled to the 45° fibre[5] pig-tailed 1×5 opto-packages. The light from a stabilized LED light source[6] with a wavelength 850 nm was coupled to the PIN diodes by the 45° angle polished fibre during proton irradiation. A constant bias voltage of −5 V was applied. The responsivity current was measured by the PC, AC/DC system and the responsivity value could be seen from a beam room monitor. We stopped the proton beams whenever the responsivity was being measured to avoid scattering light from the protons. The responsivity was measured and normalized to 1 before irradiation by adjusting the read-out factor for each channel.

The Truelight PIN diode responsivity was measured to be 0.48 A/W after coupling to a 45° fibre and 0.4 A/W for the Centronic PIN diode before irradiation. Therefore the coupling efficiency was about 80%.

4.2. Gamma source

The gamma source used was the Mega Curie ^{60}Co Irradiation Plant of the INER in Taiwan. This consists of a plane array of ^{60}Co sources covering an area of approximately $0.2\times2\,\mathrm{m}^2$. The dose rates used were 60 kGy/h. The total dose accumulated was 630 kGy for three Truelight PIN diodes and 600 kGy for the other three. This was a factor 6 times higher than that expected during the ATLAS SCT operation and reached the pixel environment. The PIN diodes were mounted on the prototype opto-packages (Section 1) and the PIN diode responsivity was measured before and after irradiation in Radiantech Inc.

5. Radiation results

The results for the proton and the gamma radiation tests are given below.

5.1. 30 MeV proton tests

Twelve Truelight PIN diodes and three Centronic PIN diodes were used in this study. The responsivity was measured during irradiation (beams were stopped when data were stored) and also after one week of annealing at a constant bias voltage of −10 V. The PIN diodes were biased with −5 V applied during irradiation. The total time taken for the irradiation was about 3 h: only a limited amount of annealing was expected to occur during this period. The results for three runs are shown in Figs. 3–5. The beam current was measured with the Faraday cup, which was about one-sixth of the beam current setting corresponding to the covered area of the beam spot.

The responsivity curves showed that both PIN diodes quickly degrade as soon as they have been

[3]ORTEC Model 439.
[4]ORTEC Model 871 timer and counter.
[5]Fujikura, S-12T-50/60/125-R. Used in SCT opto-links.
[6]Radiantech FTM-300 LED.

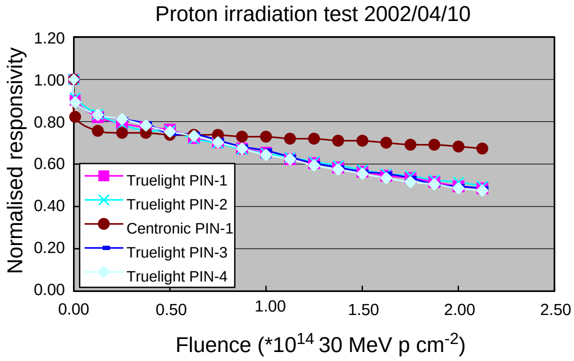

Fig. 3. Normalized responsivity for the first run from 2002/04/10 14:40 to 19:58 with a typical beam current setting of 15 nA. 2.6 nA was measured with the Faraday cup.

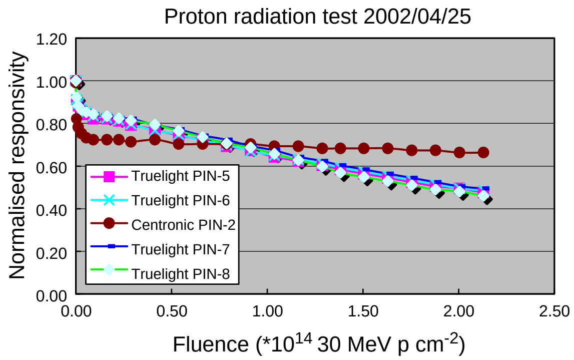

Fig. 4. Normalized responsivity for the second run from 2002/04/25 14:20 to 18:29 with a typical beam current setting of 10.1 nA. 1.3 nA was measured with the Faraday cup.

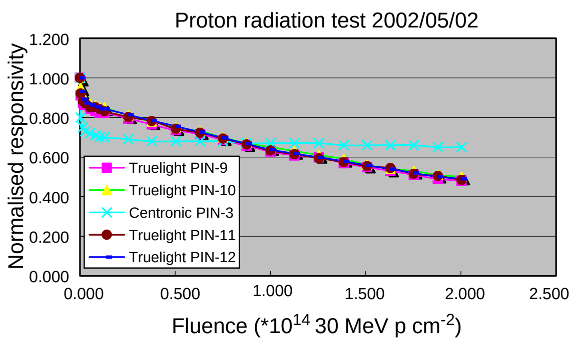

Fig. 5. Normalized responsivity for the third run from 2002/05/02 13:45 to 17:08 with a typical beam current setting of 10.5 nA. 1.8 nA was measured with the Faraday cup.

irradiated, depending on the type. The degradation linearly depends on the accumulated fluence. A typical fitting of the linear parameters β_N and R_c can be seen in Fig. 6, while the results are summarized in Table 2.

The parameters were determined to be $\beta_N = 0.0185$, $R_c = 0.16$ for the Truelight PIN diodes and $\beta_N = 0.0032$, $R_c = 0.24$ for the Centronic PIN diodes.

The non-normalized responsivity curves of the Truelight PIN diode 1 and the Centronic PIN diode 1 after coupling to the fibre pigtail are shown in Fig. 7. The responsivity of both PIN diodes degraded to 0.28 at a fluence of $1.4\times10^{14}\,\mathrm{p\,cm^{-2}}$ and to ~0.24 (50% degradation) for the Truelight

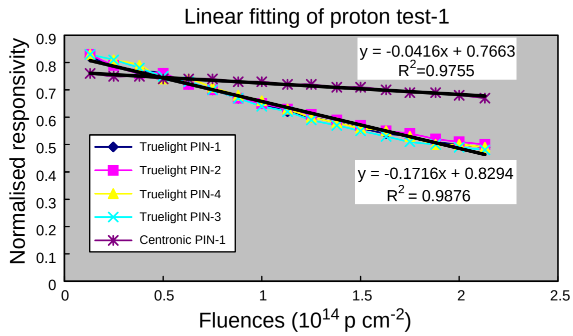

Fig. 6. Linear fit to the first runs with PIN diodes from Centronic and Truelight respectively. R is R-squared value.

Table 2
Summary of linear fits to the photodiodes responsivity curves irradiated with 30 MeV protons

Photodiodes	β_N	R_c
Truelight-1	0.0165	0.17
2	0.0172	0.17
3	0.0185	0.17
4	0.0179	0.17
Truelight-5	0.0179	0.16
6	0.0178	0.15
7	0.0181	0.14
8	0.0199	0.13
Truelight-9	0.0187	0.17
10	0.0188	0.15
11	0.0189	0.16
12	0.0186	0.17
Centronic-1	0.0042	0.23
Centronic-2	0.0031	0.18
Centronic-3	0.0024	0.30

PIN diode and ~0.27 (67% degradation) for the Centronic PIN diode at total fluences of $2.1 \times 10^{14}\,\mathrm{p\,cm^{-2}}$.

The measurements were done after 180 h of annealing (after first run). The bias voltage applied was −10 V and the illumination by stabilized LED power sources was about 20 μW. This result is shown in Fig. 8. A 2% recovery was measured from 67% to 69% for the Centronic PIN diode, and a 7% recovery from 50% to 57% for the Truelight PIN diode. However, it was noticed that only the first two or three days of annealing were helpful.

5.2. Gamma irradiation results

Six SCT prototype opto-packages, each containing two Truelight VCSELs and one Truelight PIN diode were irradiated by gamma rays to study possible dose rate effects. The dose rate was 60 kGy/h. The responsivity was measured before and after irradiation using the coupling to the 45° fibre. Tables 3 and 4 show the responsivity of the PIN diodes before and after gamma irradiation. There was no appreciable degradation of the responsivity after irradiation.

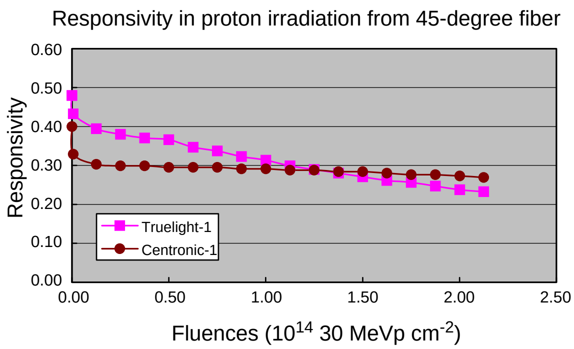

Fig. 7. The non-normalized responsivity curve of the Truelight PIN diode 1 and Centronic PIN diode 1 after coupling to the 45° fibre.

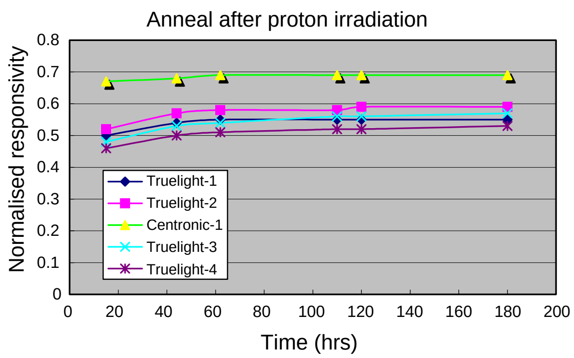

Fig. 8. Annealing test after total fluences of $2.1 \times 10^{14}\,\mathrm{p\,cm^{-2}}$. The bias voltage applied was −10 V and illumination by stabilized LED power sources was about 20 μW.

Table 3
Responsivity of PIN packages before and after gamma irradiation in the first experiment

Mrad	PIN 1	PIN 2	PIN 3
0	0.49	0.50	0.49
63	0.48	0.50	0.50

Table 4
Responsivity of PIN packages before and after gamma irradiation in the second experiment

Mrad	PIN 4	PIN 5	PIN 6
0	0.48	0.45	0.47
60	0.47	0.44	0.46

6. Conclusions

The radiation hardness of Centronic and Truelight epitaxial silicon PIN diodes was tested with 30 MeV protons up to fluences of $2.1 \times 10^{14}\,\mathrm{p\,cm^{-2}}$, equivalent to $5.7 \times 10^{14}\,\mathrm{cm^{-2}}$ 1 MeV neutron. The normalized responsivity of the PIN diodes degraded to 50% for the Truelight PIN diodes and to 67% for the Centronic PIN diodes. The responsivity including the coupling of the 45° fibre was measured as 0.24 A/W for the Truelight PIN diodes and 0.27 A/W for the Centronic PIN diodes for a fluence of $2.1 \times 10^{14}\,\mathrm{p\,cm^{-2}}$. This was 50% higher than that expected for the worst case in the pixel detector.

The linear fitting parameters were measured as $\beta_N = 0.0185$, $R_c = 0.16$ for the Truelight PIN diodes and $\beta_N = 0.0032$, $R_c = 0.24$ for the Centronic PIN diodes. However, at least 7% of the radiation damage was annealed after one week of operation at a constant bias voltage of −10 V for the Truelight PIN diodes. A reasonable estimation of the Truelight PIN diodes responsivity may be larger than 0.3 A/W after ten years operation of the pixel detector.

The gamma irradiation showed no significant degradation in the performance of Truelight PIN diodes at a dose of 600 kGy, which was a little higher than the expected ionizing radiation dose in the pixel detector. Therefore, both Truelight and Centronic PIN diodes are appropriate for use in the SCT and pixel detector applications.

Acknowledgements

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