RADIATION TESTS OF OPTICAL LINK COMPONENTS FOR THE ATLAS SCT.

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Abstract
Optical fibre and silicon epitaxial PIN photodiodes, developed for reading out the ATLAS SemiConductor Tracker, have been irradiated up to levels expected after 10 years' running at LHC. The irradiated fibre showed a negligible increase in attenuation. The DC and AC response of the photodiodes remained at acceptable levels. Progress on aging tests is reviewed.

1. INTRODUCTION

The architecture and the overall performance of the optical links to be used for reading out the ATLAS SemiConductor Tracker have been described in earlier contributions [1,2]. A crucial issue is the radiation hardness of various components of the links. For the SCT, lying between 20cm and 52cm from the beamline, ten years of LHC operation are equivalent to up to 1.3 10^{14} (1MeV) neutrons cm^{-2}. The bulk radiation damage depends on the Non Ionising Energy Loss (NIEL) experienced by the incident particle in the material [3]. Since the NIEL depends on both the incident particle type and energy as well as the material involved, the effective fluence of particles is expressed in terms of an equivalent number of 1MeV neutrons. This convention is used throughout the paper.

The ionisation deposited in the silicon of the SCT amounts to 100kGy (10MRad). For the pixel detectors, which lie closer to the beamline, the fluence and dose are significantly higher : up to 5 10^{14} (1MeV) neutrons cm^{-2} and up to 300kGy (30MRad).

A schematic of the SCT links is shown in figure 1. Data are transmitted from detector modules to the control room while Timing, Trigger and Control signals are sent from the control room to the detectors. All apparatus from the detector modules to the patch panel must be capable of surviving the radiation levels described above. Also the links must function at rates of 40M bits per second.

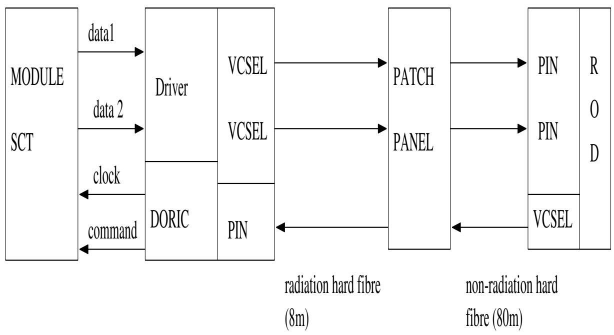

Figure 1. A schematic diagram of the ATLAS SCT links.

This paper describes the radiation hardness of Fujikura optical fibre and of Centronic silicon PIN photodiodes up to levels corresponding to 10 years running at LHC. The radiation hardness of VCSELs and Driver/DORIC circuits has been discussed at previous Workshops[4].

2. IRRADIATION OF FUJIKURA FIBRE

A sample of Fujikura[1] 50/60/125/250 optical fibre[2], 12m long, was irradiated by gamma rays, using the "1 curie" Co-60 source at the University of Birmingham Radiation Centre. The gamma rays had a mean energy of 1.25MeV. The fibre was irradiated overnight and during weekends for two months until the total dose received amounted to 300kGy, the level expected for the innermost layer of the pixels after 10 years of LHC operation. The attenuation of the fibre was measured regularly using an LED light source

[1] Fujikura, Optical Fiber Products Div.,1-5-1 Kiba, Koto-ku, TOKYO 135, Japan.
[2] A step-index multimode fibre comprising: a pure silica core (radius 25um); 5um of fluorine doped depressed refractive index cladding; pure silica cladding out to radius of 62.5um and finally a protective jacket out to 125um.

(850nm, 3µW<power<16µW) and is plotted in figure 2. For doses up to 300kGy, the attenuation induced by the irradiation is negligible.

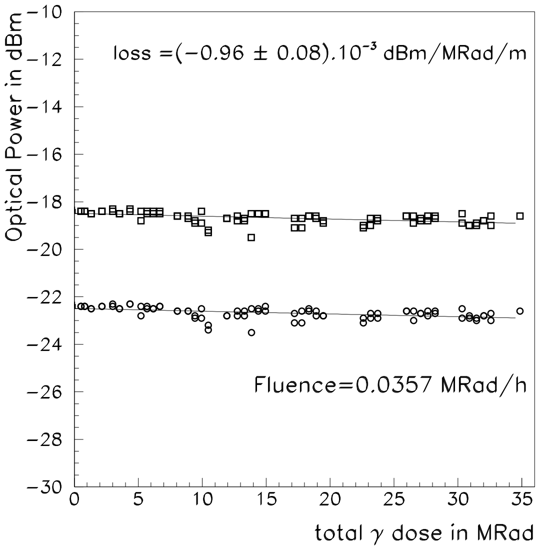

Figure 2. . The power transmitted through the Fujikura optical fibre versus the received dose of ionising radiation. The two horizontal distributions correspond to different light levels transmitted through the fibre.

A similar sample of Fujikura fibre was irradiated with an equivalent of 10^{15} (1MeV) neutrons at the Ljubljana reactor centre. This fluence induced an attenuation of only 0.13dB/m.

We conclude therefore that the Fujikura 50/60/125/250 fibre is entirely satisfactory; it shows a radiation hardness almost an order of magnitude larger than that required for the ATLAS SCT optical links.

3. IRRADIATION OF PHOTODIODES

Sets of Centronic[3] silicon photodiodes, operating at 850nm, have been irradiated with neutrons and protons during the last two years. In 1997, the first irradiations showed that Si photodiodes produced by an epitaxial process were encouragingly radiation hard [4]. These photodiodes were mounted in sets of three on the GEC [4]packages [1] (in which the alignment of optical fibres with photodiodes is performed using “V groove” technology). Three GEC packages, containing 9 devices, were irradiated. Their dark currents and DC response were measured while the devices were being irradiated; this allowed the performance of the photodiodes to be monitored online.

In 1998, a different procedure was adopted. Sets of 8 silicon photodiodes were mounted on ceramic tiles and were measured only before and after the irradiation. The photodiodes are measured using the scanning machine, developed by the Berne group [5]. (This apparatus enables an LED light source to be moved in precise steps across sets of photodiodes; the position of maximum signal is found for each photodiode and the dark current and DC response are then measured). The Berne machine was transported to Birmingham early in 1998 in order to continue its use in the characterisation of large numbers of devices.

3.1 Results from the 1997 irradiation.

Nine epitaxial Si photodiodes were irradiated first with neutrons from the Dynamitron at the Birmingham University Radiation Centre (neutron energy centred around 2 MeV). Since the neutrons were emanating from effectively a point source, the irradiated photodiodes experienced significantly different fluences. Then the same devices were irradiated at the ISIS spallation source at the Rutherford Laboratory (which produced neutrons of energy centred around 1MeV). Later in the year, the photodiodes were irradiated along with ATLAS SCT silicon microstrip detectors by 26GeV protons at the CERN PS. For the proton run only, the photodiodes were placed in a box, cooled to –10°C, which was scanned through the beam in order to irradiate all items uniformly.

During the irradiations at Birmingham and CERN, light from an LED was fed via optical fibres into each photodiode so that the dark current and DC response of each device were monitored online. This was not feasible at ISIS where the characteristics of the photodiodes could be measured only before and after irradiation.

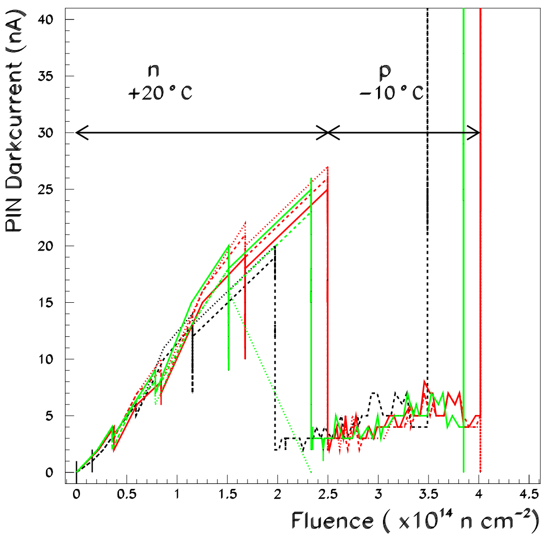

Figure 3. Darkcurrent versus fluence. The vertical lines indicate series of measurements when the devices were not being irradiated but were operated at different temperature. (During the irradiation at the Dynamitron, the PINs received different fluences).

[3] Centronic, Electro-Optics Division, Centronic House, Croydon, UK.
[4] GEC-Marconi, Caswell, Towcester, Northants NN12 8EQ, UK.

The increase in dark current with accumulated fluence is shown in figure 3 above. During the neutron irradiation at room temperature, the dark current increased from a few nA to approximately 25nA. In the proton irradiation, carried out at about –10°C, the dark current falls by a factor 10 approximately as expected due to the lower temperature, before rising in proportion to the total fluence received.

The dark currents observed are completely negligible compared to the magnitude (≥ 0.1mA) of the expected signals.

In figure 4, the photodiode response is plotted versus time. Initially, the response of the devices is about 0.36A/W (cf the response of a photodiode, operating with 100% quantum efficiency at 850nm, would be 0.68A/W).

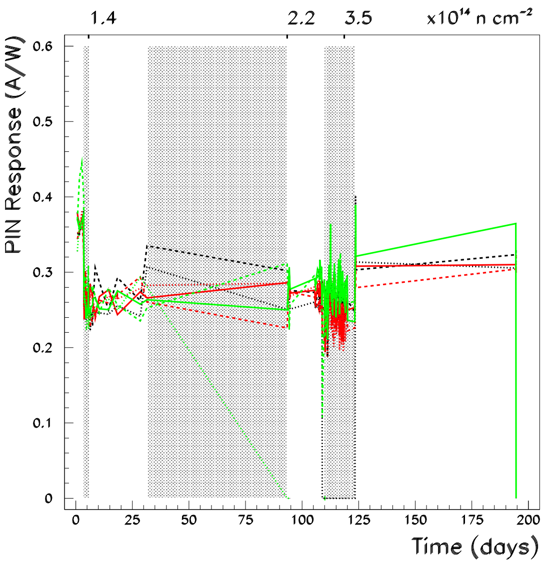

Figure 4. The response of each photodiode is plotted against time. The shaded regions denote the three periods of irradiation, described in the text.

The performance of the photodiodes is shown in more detail in figure 5. The response drops by about 30% at the first bout of irradiation and then remains constant thereafter, with no further degradation seen even up to the highest fluences expected for the pixel detectors.

The picture is very encouraging. The photodiodes are sufficiently radiation hard to withstand fluences up to 4. 10^{14} (1MeV) neutrons cm^{-2}. Further tests will show whether the devices can survive the fluences expected for the innermost pixel detectors.

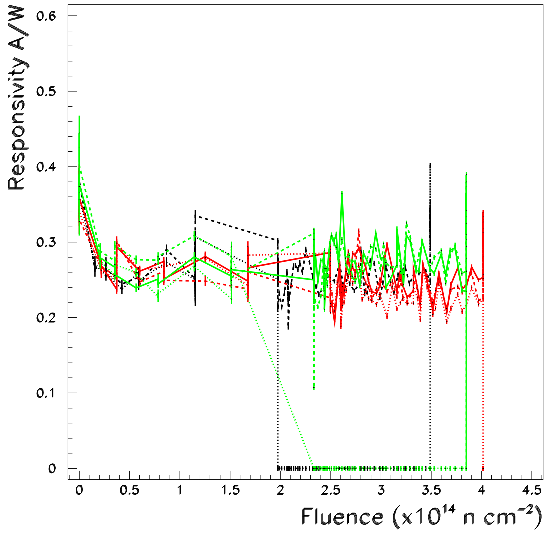

Figure 5. The response of the PIN diodes is plotted against the fluence received. The fluences are given in terms of equivalent neutrons of 1MeV energy, as described in the text.

The AC response of the photodiodes is similarly satisfactory. In figure 6, we see that, at bias voltages above 5V, an upper limit of the response time of the device (limited by the measuring apparatus) is about 1ns. This is adequate for the ATLAS SCT links which will operate at 40MHz.

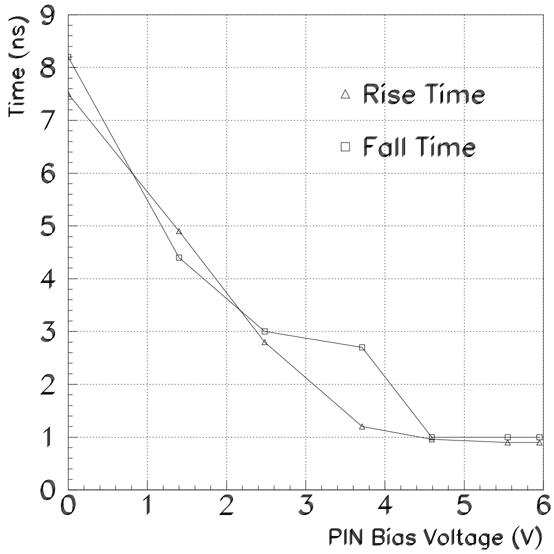

Figure 6. The rise and fall times of irradiated photodiode signals (in response to an instantaneous light pulse) are plotted against the applied bias voltage.

3.2 *Results from the 1998 Irradiation.*

Twelve tiles of photodiodes, containing 96 PIN devices, were irradiated by neutrons in ISIS at the Rutherford Laboratory. The total fluence was measured (using activated foils) to be $(1.45\pm0.05)10^{14}$ (1MeV) neutrons cm^{-2}.

During the irradiation (at room temperature), the diodes were biased but were not read out. The dark current per photodiode increased from several nA before irradiation to values in the range, 10nA to 20nA, after irradiation. This increase is quite consistent with results obtained in 1997 (figure 3).

On the other hand, a larger drop in response was observed, compared to the 1997 results. In figure 7, the responses of a set of irradiated and non-irradiated photodiodes are plotted. (A direct comparison of response for the same photodiodes, before and after irradiation, was not performed since the LED light source on the Berne machine had been replaced). In figure 7, the two sharp peaks indicate that the devices in each set perform very similarly. The response after irradiation has fallen to a factor, 0.46±0.05, of the response before irradiation.

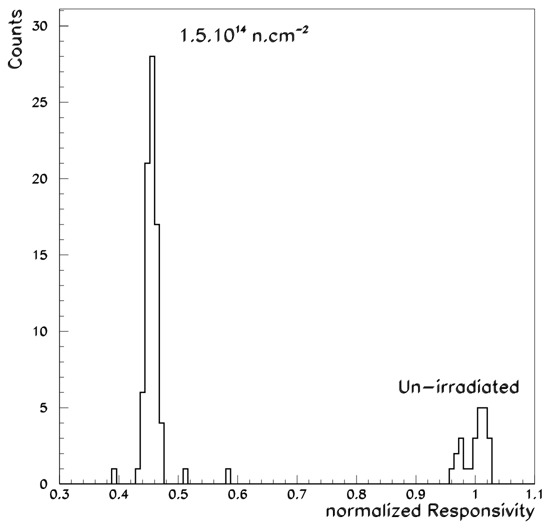

Figure 7. The response of sets of photodiodes, non-irradiated and irradiated with neutrons, as described in the text.

This is a more significant reduction than the 1997 results which suggested a degradation by a factor, (0.70±0.05), for even larger fluences. This discrepancy is thought to be due to the LED/PIN layout within the Berne scanning machine. At the standard separations between LED source and PIN diode receiver, the emitted light forms an envelope larger than the photodiode diameter (375µm). Therefore, as the LED light produces charged carriers throughout the silicon volume of the photodiode, a significant fraction of the diode response is due to charges outside the region of high electric field in the depletion layer. The collection of these extraneous charges is expected to be more strongly affected by radiation damage in the silicon than the charges produced in the active volume of the device. The data of 1997 will not be sensitive to this effect since, in those tests, the LED light was channelled directly to the active area of the photodiode via optical fibres.

As a check of this hypothesis, a photodiode, which was irradiated in 1998 and which showed a fall in response of a factor 0.46, was illuminated with light from a VCSEL (which illuminated an area smaller than the active area of the device). Results are shown in figure 8. We see that the non-irradiated photodiode operates efficiently at very low bias while the irradiated device commences efficient operation only above a bias of 3.5V. This behaviour is qualitatively similar to that observed with silicon detectors; during irradiation, "type inversion" occurs so that the initial intrinsic silicon becomes increasingly p type. As the charge carrier density rises, the applied bias voltage must be increased in order to deplete fully the material.

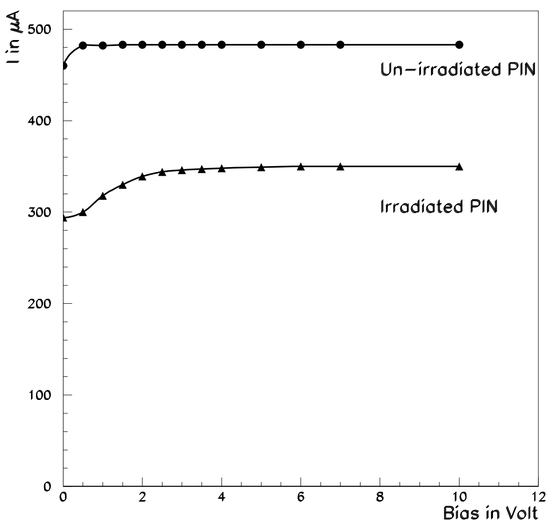

Figure 8. For constant incident light, the currents produced by an irradiated and an unirradiated photodiode are plotted against the applied bias.

We see that the plateau value of response has fallen to around 70% after irradiation. As a further crosscheck, several photodiodes from a different manufacturer but made using the same process, were irradiated by 4. 10^{14} (1MeV) neutrons cm^{-2} in Ljubljana.

These too showed a 30% only fall in response. We conclude that the discrepancy between the 1997 and 1998 results is due to the mismatch in light,emitted by the LED and received by the photodiodes, in the Berne machine.

Since the observed 30% degradation in PIN diode response is negligible given the large light levels produced by VCSELs, the PIN diodes seem entirely adequate for the ATLAS SCT links.

3.3 Further irradiation tests (1998)

During September 1998, three tiles (each containing 8 photodiodes which had already been irradiated by neutrons in ISIS) were exposed to 24GeV protons at the CERN PS. The devices were irradiated along with a batch of silicon microstrip detectors and so were maintained at a temperature of about –10°C. The total fluence received was 2.8 10^{14} protons cm^{-2} (corresponding to 1.6 10^{14} (1MeV) neutrons cm^{-2}). Once the induced radioactivity in the photodiodes is sufficiently low, they will be remeasured in Birmingham.

In late September, three tiles, containing 24 photodiodes were returned to ISIS to be irradiated again with neutrons.

After this second round of irradiation, by protons and by neutrons, we shall check that the response of the PIN diodes has not degraded further (as expected from the 1997 results). Results will confirm (or not) on a larger sample than in 1997 whether the photodiodes can survive radiation up to the levels expected for the pixel detectors.

4. AGING TESTS

A prototype testsetup is operational whereby each of the 8 photodiodes of an unirradiated tile is coupled via optical fibre to its own VCSEL. The VCSELs supply about 1mW of optical power continuously to each device. After 40 days operation, no major problems have occurred. The apparatus is now being constructed so that 96 irradiated PIN diodes can be subjected to long term aging tests.

5. CONCLUSIONS

The ATLAS SCT irradiation programme has led to the following conclusions :

- The Fujikura optical fibre (50/60/125/250) is radiation hard well beyond the required level.
- The optical receivers (Centronic PIN silicon epitaxial photodiodes) showed a degradation of response of approximately 30% in the 1997 tests and of 54% in 1998. Further tests will be carried out to confirm whether the lower result in 1998 is due to the systematic bias in the setup, described in section 3.2. Given the large levels of light available if VCSELs are used as optical transmitters, this fall in response is acceptable for operation in the SCT and pixel readout. The darkcurrents after irradiation are negligible compare to the expected signal size.
- The electrical drivers and receivers (LDC and DORIC) are adequately radiation hard [1].
- Aging tests have begun; preliminary results are encouraging.

We conclude that the ATLAS SCT/Pixel readout, based on 850nm optical links, can survive the fluences, expected after 10 years of LHC operation; the complete system appears feasible.

6. ACKNOWLEDGEMENTS

We are very grateful for the expert technical assistance of Dennis Grant, Roger Harris and Ian McGill in Birmingham and of Derrick Hill at RAL. We thank the UK Particle Physics and Astronomy Research Council for financial assistance.

7. REFERENCES

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