Characterisation of p-in-n ATLAS silicon microstrip detectors fabricated by Hamamatsu Photonics and irradiated with 24GeV/c protons to 3×10^{14}pcm^{-2}.

D. Morgan [a 1] C.M. Buttar [b] J.R. Carter [a] I.Dawson [b] K. Hara [c] R. Harper [b] Y. Iwata [d] T. Kohriki [e] T. Kondo [e] T. Ohsugi [d] D. Robinson [a] M. Shimojima [c] S. Terada [e] Y. Unno [e]

[a] *Cavendish Laboratory, The University of Cambridge, UK*

[b] *Department of Physics, The University of Sheffield, UK*

[c] *Department of Physics, The University of Tsukuba, Tsukuba 305-8571, Japan*

[d] *Department of Physics, Hiroshima University, Higashi-Hiroshima 739-8526, Japan*

[e] *KEK, High Energy Accelerator Research Organization, Tsukuba 305-0801, Japan*

Abstract

P-in-n silicon microstrip prototype detectors for the ATLAS experiment at CERN have been designed and manufactured by Hamamatsu Photonics. Detectors were irradiated at the CERN Proton Synchrotron facility to a fluence of 3×10^{14} pcm^{-2}, corresponding to the total fluence anticipated after ten years of operation in the ATLAS semiconductor tracker. They were subsequently annealed for 7 days at 25^{o}C in order to reach the end of the beneficial annealing period and hence the minimum in depletion voltage. The characteristics of 4 different detector designs have been evaluated. The pre-irradiation behaviour of all detectors is consistent and well within the specifications for ATLAS detectors. Similarly, the post-irradiation and anneal performance for all detectors shows excellent behaviour. This is in terms of both the leakage current characteristics and the signal and noise performance as determined from LHC speed readout electronics. The detector characteristics are such that operation within the maximum operating voltage envisaged for ATLAS is possible.

[1] Corresponding Author

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1 Introduction

The ATLAS experiment (1) at CERN is a general purpose proton-proton detector currently being designed for the Large Hadron Collider (LHC). The central region of the detector will consist of 63m^2 of silicon microstrip detectors, all of which will receive unprecedented levels of radiation during the lifetime of the experiment. After 10 years of operation the estimated maximum fluence for detectors closest to the beam pipe is 1.4×10^{14} 1 MeV equivalent neutrons cm^{-2} (2).

Silicon detectors being developed for this experiment consist of p-type microstrips fabricated on n-bulk silicon. The extreme levels of radiation during the experiment will cause type inversion to take place within the silicon bulk early on in the experiment lifetime. This will cause the detector junction to move to the back side of the detector after inversion. The detector must therefore be fully depleted in order that charge is efficiently collected on the strips.

Irradiated silicon will in addition anneal at temperatures above 0^oC (3; 4). On a shorter time scale the annealing is dominated by the recombination of radiation induced acceptor sites into inactive sites, causing the detector depletion voltage to decrease with time. At much longer time scales acceptor sites become active, and the depletion voltage increases with time. Both the beneficial and anti-annealing periods are temperature dependent and annealing effects can be suppressed by operating detectors below 0^oC. It is for this reason that ATLAS will be maintained at $-8^o\text{C}\pm1^o\text{C}$ whilst in operation. However, as detailed in (2), yearly warm-up periods are foreseen during the lifetime of the experiment. These have been simulated using the Ziock parameterisation (5) and detectors in this study have been annealed for 7 days at 25^oC in order to reach the minimum in detector depletion voltage.

2 Detectors in the Study

All detectors in this study were prototype detectors for the barrel region of ATLAS and were manufactured by Hamamatsu Photonics (6). The detector size was $64 \times 63.6\text{mm}^2$, with an active area of $62 \times 61.6\text{mm}^2$, and all detectors consisted of 768 AC coupled p-type readout strips with an 80μm pitch. The detector thickness was either 305μm or 325μm. All strips were polysilicon biased with a resistance of $\approx 1.5\text{M}\Omega$. Detectors were fabricated on $< 111 >$ orientation silicon.

Nine detectors in the study were fabricated using the Hamamatsu baseline design whereby the width of the aluminium contact layer was 6μm less than the implant width. This design had been fabricated previously and the detectors had been shown to be fully operational after heavy irradiation and annealing. However, when operated at a bias in excess of 400V the detectors showed signs of micro-discharge. Three optimised barrel designs were thus fabricated to try to eliminate micro-discharge effects at high bias. The optimised designs were as follows:

- Wide Aluminium: The implant layer was decreased and the aluminium layer increased in order that the aluminium exceeded the implant by 3μm on either side.
- Wide Polysilicon: A polysilicon layer was introduced between the implant and the metal layer with the width of the polysilicon exceeding that of the implant by 3μm.
- Narrow Polysilicon: Similar to the wide polysilicon design, with the width of the polysilicon layer equal to the implant width.

Typical pre-irradiation leakage currents for all detectors were of the order of a few hundred nA at 350V. The detector depletion voltages were around 80V.

3 Irradiation and Annealing

All detectors were irradiated at the CERN Proton Synchrotron facility using 24 GeV/c protons to a fluence of 3×10^{14} pcm^{-2}. This is the maximum fluence expected after 10 years of operation, taking into account a proton hardness factor of 0.69 and a contingency in the fluence estimation of 50%. The detectors were placed in a cool box during the irradiation and maintained at a temperature of -8^{o}C. A bias of 100V was applied and the strip metals were grounded throughout the irradiation. Homogeneous irradiation of the full detector area was achieved by placing the cool box on an XY stage, allowing the detector area to be scanned by the proton beam. Once the irradiation was complete, the detectors were stored at -10^{o}C.

Controlled annealing of the detectors then took place using a method similar to that described in (7). Detectors were annealed to the point of minimum depletion voltage i.e. after the beneficial annealing period was complete and before the anti-annealing period had begun. This was done by controlled heating at 25^{o}C for a period of 7 days. All detectors were then transported to the UK in order that measurements could be carried out.

4 Detector Measurements

4.1 Leakage Current Characteristics

The leakage current characteristics for all detectors is shown in figure 1. Measurements were taken up to a bias voltage of 500V, and at a temperature of -18^{o}C. The leakage current stability of some of the detectors has been measured at 350V bias and a temperature of -18^oC. This was monitored over a 24 or 64 hour period and results can be seen in figure 2.

4.2 Strip Quality Analysis

The strip quality for each detector was determined using a probe station. Pinholes in the oxide were identified when a significant increase in the strip leakage current was observed. Shorts between the strip metals and discontinuities were identified from capacitance measurements on the strips. Results from these measurements can be seen in table 1.

4.3 Analogue Readout

128 channels from each detector were bonded to a FELIX128A analogue readout chip (8). Using a Ru-106 β source the signal was measured as a function of bias. From this measurement the corresponding charge collection efficiency could be evaluated. An estimation of the depletion voltage after irradiation could then be determined, given as the onset of the plateau in the plot of charge collection efficiency versus bias. Figure 3 shows the charge collection efficiency and noise results for the baseline, the wide aluminium and the wide polysilicon detector designs. Note that the errors correspond to the RMS distribution of the collected signal.

4.4 Binary Readout

Binary readout hybrids populated with LBIC (9) and CDP (10) readout chips were used to determine the strip quality on each detector. The noise occupancy per channel was determined for a range of thresholds and the noise as a function of detector bias was determined. Figure 4 shows the variation in noise for each of the detector designs. The results correspond to one of the chips on the hybrid, i.e. 128 channels. Note that the electron noise level cannot be taken as absolute since it is dependent on the binary readout hybrid used.

5 Discussion

In figure 1 the leakage current behaviour for all detectors is similar up to an applied voltage of 400V. The leakage currents have increased significantly during irradiation, as expected, with the level at 350V now around 0.15mA for all detectors. At higher bias some of the detectors, in particular the narrow polysilicon design, appear to show an increase in leakage current and this has been defined as micro-discharge. Most noticeable is the wide aluminium detector where any micro-discharge effects appear to be suppressed. The leakage current stability results in figure 2 show no deviation in the current over the time period measured.

From the strip quality measurements shown in table 1 it can be seen that no degradation in either the strip metal or oxide layer has occurred during the irradiation and subsequent annealing.

Results obtained from the analogue measurements, as shown in figure 3, indicate that a plateau in the charge collection efficiency occurs at around 300V for the detectors measured. This therefore gives an indication of the bias that will be required to achieve maximum charge collection efficiency during the experiment. Measurements taken with the binary readout give an indication of the variation of noise with detector bias. From the results shown in figure 4 it can be seen that all detectors, apart from the wide polysilicon design, exhibit decreasing noise for an increasing bias up to 500V.

6 Conclusions

A selection of p-type strip on n-bulk silicon microstrip barrel detectors were irradiated to 3×10^{14}pcm^{-2} and annealed for 7days at 25^{o}C and their post irradiation characteristics determined. Four different designs were characterised, each having a variant of either the width of the aluminium layer or having an additional polysilicon layer. All detectors have been shown to have excellent all round performance after irradiation. In order to quantify the optimised design sufficiently, and compare performance with the baseline design, it is necessary to increase the statistics. The irradiation, annealing and quantification of further detectors is already in progress.

7 Acknowledgements

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Figures and Tables

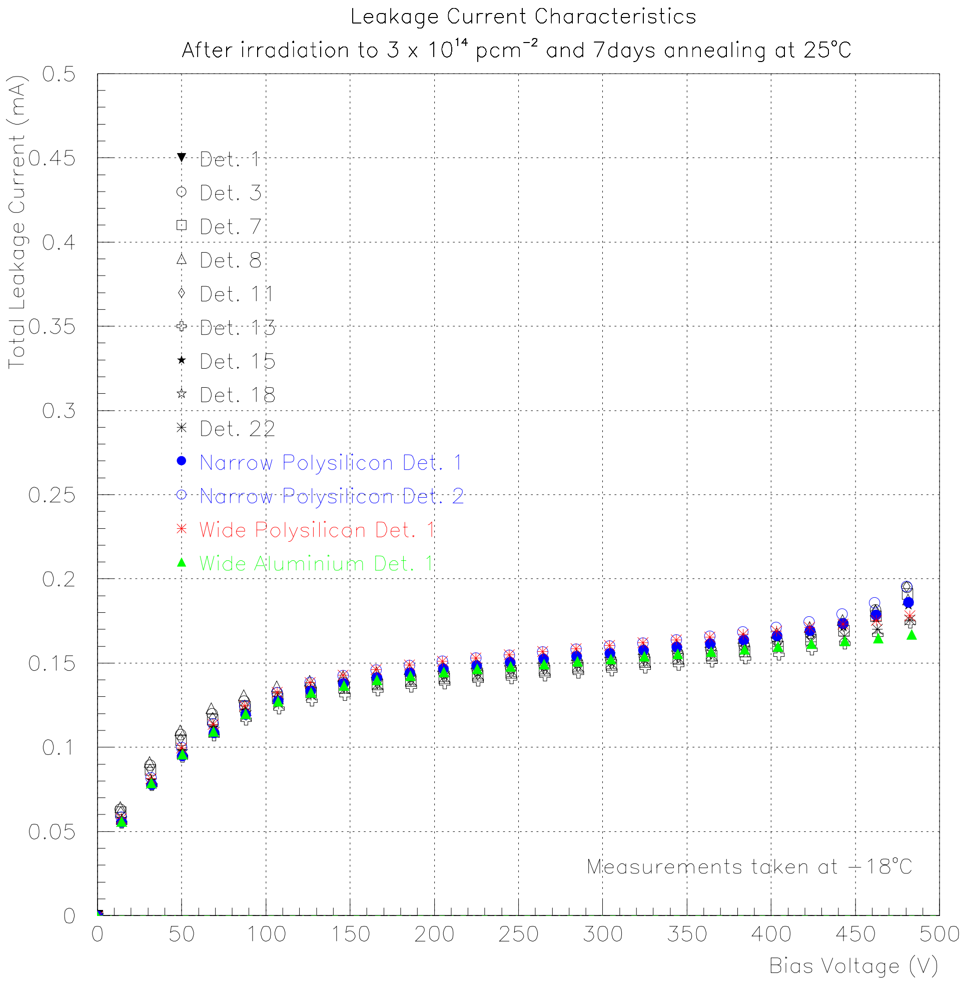

Fig. 1. Leakage current characteristics for all detector designs after irradiation and annealing.

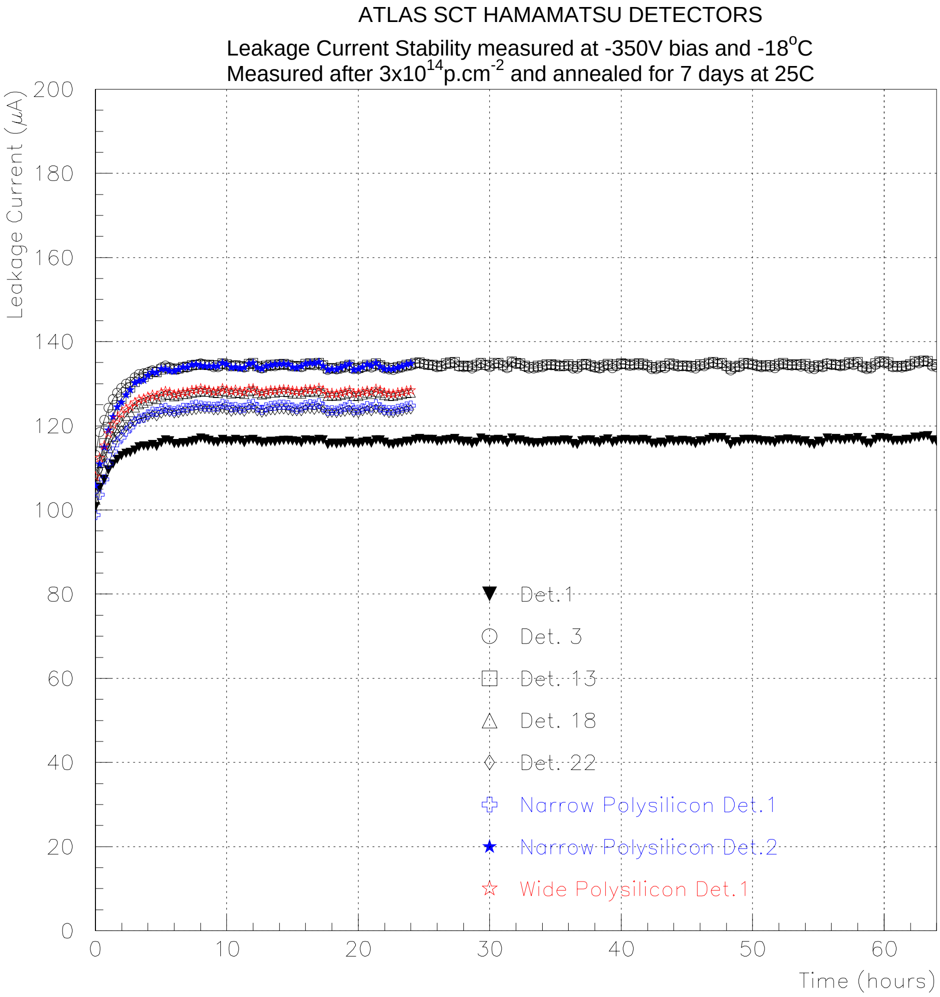

Fig. 2. Stability of the leakage current at 350V and at -18^{o}C.

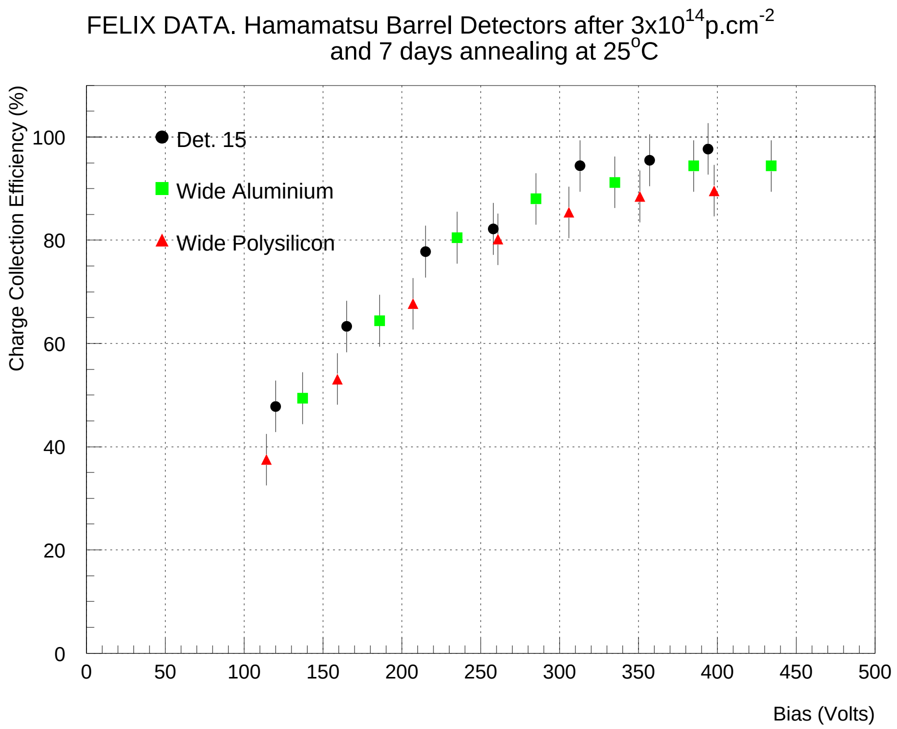

Fig. 3. Analogue readout measurements using a FELIX128A readout chip.

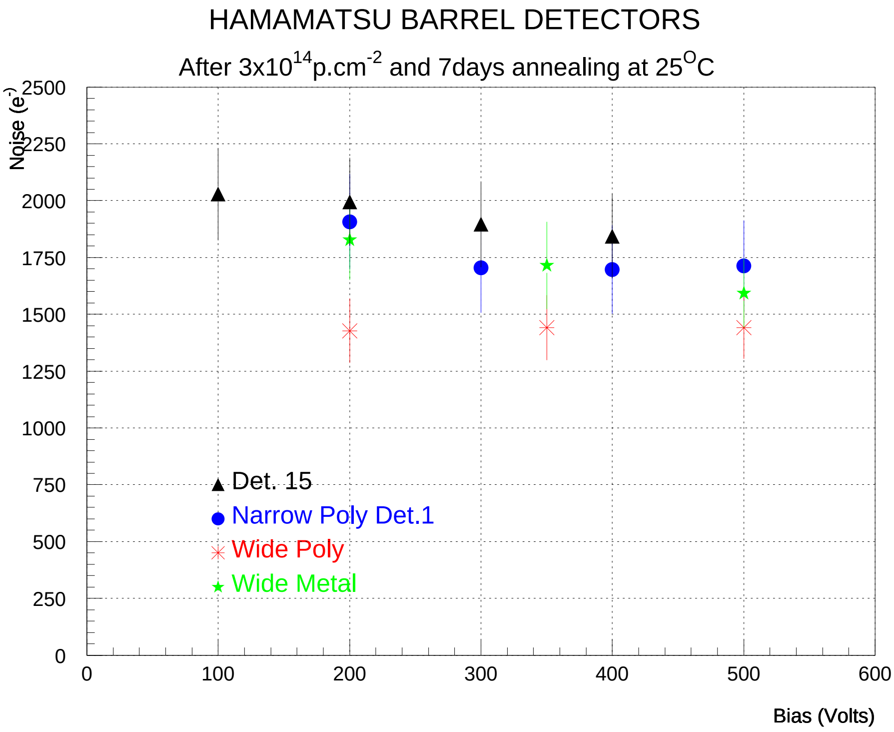

Fig. 4. Noise as a function of bias measured using CDP and LBIC binary readout chips.

Detector	Opens	Shorts	Pinholes (Pre-Irradiation)	Pinholes (Post-Irradiation)
Det.1	0	0	5	1
Det.3	0	0	0	0
Det.7	0	0	0	0
Det.8	0	0	0	0
Det.11	0	1	0	0
Det.13	0	0	0	0
Det.15	0	0	0	0
Det.18	0	0	0	0
Det.22	0	0	0	0
Narrow Poly 1	0	0	0	0
Narrow Poly 2	0	0	0	0
Wide Poly	0	0	0	0
Wide Aluminium	0	0	0	0

Table 1
Strip quality analysis for irradiated and annealed detectors.