Nuclear Instruments and Methods in Physics Research A 450 (2000) 297–306

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.nl/locate/nima

A comparison of the performance of irradiated p-in-n and n-in-n silicon microstrip detectors read out with fast binary electronics

P.P. Allport[a], L. Andricek[b], C.M. Buttar[c], J.R. Carter[d,*], M.J. Costa[e], L.M. Drage[d], T. Dubbs[f], M.J. Goodrick[d], A. Greenall[a], J.C. Hill[d], T. Jones[a], G. Moorhead[g], D. Morgan[c], V. O'Shea[h], P.W. Phillips[i], C. Raine[h,✠], P. Riedler[j], D. Robinson[d], A. Saavedra[k], H.F-W. Sadrozinski[f], J. Sánchez[e], N.A. Smith[a], S. Stapnes[l], S. Terada[m], Y. Unno[m]

[a]*Oliver Lodge Laboratory, University of Liverpool, Liverpool, L69 3BX, UK*
[b]*Max-Planck-Institut für Physik, Munich, Germany*
[c]*Department of Physics, University of Sheffield, Sheffield, S3 7RH, UK*
[d]*Cavendish Laboratory, University of Cambridge, Madingley Road, Cambridge, CB3 0HE, UK*
[e]*IFIC, University of Valencia - CSIC, E-46100 Burjassot Valencia, Spain*
[f]*SCIPP, University of California, Santa Cruz, CA, USA*
[g]*Research Centre for High Energy Physics, University of Melbourne, Australia*
[h]*Department of Physics and Astronomy, University of Glasgow, UK*
[i]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, UK*
[j]*EP Division, CERN, CH-1211 Geneva 23, Switzerland*
[k]*School of Physics, University of Sydney, Australia*
[l]*University of Oslo, Oslo, Norway*
[m]*KEK National Laboratory for High Energy Physics, Tsukuba 305-0801, Japan*

Received 14 December 1998; received in revised form 21 December 1999; accepted 17 January 2000

Abstract

Both n-strip on n-bulk and p-strip on n-bulk silicon microstrip detectors have been irradiated at the CERN PS to a fluence of 3×10^{14} p cm^{-2} and their post-irradiation performance compared using fast binary readout electronics. Results are presented for test beam measurements of the efficiency and resolution as a function of bias voltage made at the CERN SPS, and for noise measurements giving detector strip quality. The detectors come from four different manufacturers and were made as prototypes for the SemiConductor Tracker of the ATLAS experiment at the CERN LHC. © 2000 Elsevier Science B.V. All rights reserved.

PACS: 29.40

Keywords: Irradiated; Silicon; Microstrip; Detectors

* Corresponding author. Tel: +44-1223-337235; fax: +44-1223-353920.
E-mail address: jrc1@hep.phy.cam.ac.uk (J.R. Carter).
✠ Deceased.

PII: S0168-9002(00)00259-X

1. Introduction

Silicon microstrip detectors are widely employed to provide precision tracking of charged particles. At the future CERN Large Hadron Collider (LHC) such detectors will operate in high-radiation environments, and will need to maintain good efficiency throughout the lifetime of the experiment. In this paper we present comparative results on the performance of detectors prototyped for the SemiConductor Tracker (SCT) of the ATLAS experiment at the LHC, following their irradiation to a fluence of 3×10^{14} p cm^{-2} 24 GeV/c protons, equivalent to the maximum anticipated dose during the lifetime of the experiment.

In the design of the ATLAS SCT, microstrip detectors with single-sided readout are glued back to back on a high thermal conductivity baseboard [1]. The strips are AC capacitively coupled to fast single-strip threshold binary readout electronics. The detectors are fabricated on a substrate of high-resistivity n-type silicon. The choice of two different detector readout technologies is available; n^+-strip readout (n-in-n detectors) or p^+-strip readout (p-in-n detectors).

Both p-in-n and n-in-n full-sized detectors have been prototyped, and their post-irradiation performance measured in a test beam at the CERN SPS. Results on efficiency, resolution and the readout quality of the strips are presented for detectors of each type, coming in total from four different manufacturers.

2. p-in-n and n-in-n detectors

At the irradiation levels to be experienced at the LHC, the silicon detectors will undergo type inversion from n- to p-type early in the lifetime of the experiment. The reverse annealing of the depletion voltages that follows initial beneficial annealing is a strong function of temperature. The ATLAS SCT will be maintained at low temperature (-7°C) to suppress this reverse annealing, but annual warm-up periods are anticipated for maintenance. Reasonable estimates suggest that the maximum depletion voltage in the SCT after 10 years of operation of the experiment will be over 400 V [1] for 300 μm thick detectors.

An advantage of n-in-n detectors in this environment is that the bulk silicon depletes from the strip side following type inversion, and so signal collection is assured even if the bulk is only partially depleted. Efficient operation of 300 μm thick n-in-n detectors after irradiation has been measured at voltages as low as half the depletion voltage [2–4]. In contrast, depletion grows from the back plane after type inversion for p-in-n detectors. It would therefore be expected that such detectors need to be operated close to, or above, their depletion voltage. Below depletion, a reduced signal is still produced in the readout strips by induction across the undepleted, high-resistivity bulk [5]. However, the increase in the spatial extent of this signal as the voltage is lowered will lead to reduced efficiency, especially when using single-strip threshold binary readout electronics.

Thus n-in-n detectors offer the possibility of a system design with lower post-irradiation operating voltages. However, they require double-sided processing and are more expensive to produce than p-in-n detectors. The measurements reported here were undertaken in order to quantify the differences in efficiency as a function of voltage of irradiated p-in-n and n-in-n detectors, to study spatial resolution, and to establish the detector readout strip quality after irradiation.

3. The irradiated detectors

Samples of 18 n-in-n detectors and seven p-in-n detectors were irradiated at the CERN PS to a fluence of 3×10^{14} p cm^{-2} 24 GeV/c protons, equivalent to approximately 1.5×10^{14} 1 MeV n cm^{-2}. The detectors had their strip metal and underlying implanted strips connected to ground, as would be the case in the ATLAS experiment, and their backplanes were biased to 150 V during irradiation. They were maintained at a temperature of $-8\pm1^\circ$C in a nitrogen atmosphere. Each detector was either glued or clamped to a ceramic support frame, and uniform irradiation over the whole detector area was ensured by scanning across the beam on an X–Y stage. From this

Table 1
Some characteristics of the detectors under test

Code	Detector type	Supplier	Wafer thickness (μm)	p-stops	Pre-irradiation Depletion volts (V)
N1	n-in-n	SINTEF[1]	300	Individual	42
N2	n-in-n	Hamamatsu Photonics[2]	300	Individual	60
N3	n-in-n	Hamamatsu Photonics[2]	300	Common + field plate [7]	70
P1	p-in-n	SINTEF[1]	300	–	55
P2	p-in-n	Eurisys[3]	340	–	40
P3	p-in-n	MPI[4]	280	–	100

[1] SINTEF, P.O. Box 124, Blindern, N-0314 Oslo, Norway.
[2] Hamamatsu Photonics, 1126-1 Ichino-cho, Hamamatsu 435, Japan.
[3] Eurisys Mesures, 1 Chemin de la Roseraie, Lingolsheim, BP 311-67834 Tanneries, Cedex, France.
[4] Max Planck Institut für Physik, Postfach 401212, Foehringer Ring 6, D-80805 Munich, Germany.

irradiated sample, five representative n-in-n detectors and four p-in-n detectors were subjected to controlled thermal annealing corresponding to 21 days at 25°C. This is equivalent to the warm up time estimated to be required for detector maintenance during 10 years of ATLAS operation at the LHC. Detector current and capacitance measurements made during the annealing process are described elsewhere [6].

Three n-in-n and three p-in-n irradiated and annealed detectors were selected for connection to readout electronics and test-beam measurement. This subset was chosen as being representative both of the suppliers and the range of different designs. All detectors had overall dimensions of $64.0\ \text{mm} \times 63.6\ \text{mm}$ and an active area of $62.0 \times 61.6\ \text{mm}^2$, with 768 AC-coupled readout strips at a pitch of 80 μm. The detectors were from four separate suppliers and had differing thicknesses, initial bulk resistivity, edge termination designs, biasing resistors and passivation. Two of the n-in-n detectors were fabricated with conventional p-stops between the readout strips to break the surface electron accumulation layer, while the third had a novel isolation technique [7] which used polysilicon field plates in DC contact with a common p-frame. Some detector properties are summarised in Table 1.

4. Detector readout

After irradiation, the 768 approximately 6 cm long strips of each detector were connected for readout to unirradiated fast front-end electronics. In the ATLAS SCT, pairs of detectors will be bonded together giving 768 approximately 12 cm long strips. For the present tests, sets of pitch adaptors were used to allow the investigation of both 6 and 12 cm long strip properties using a single detector and 512 readout channels. The readout assembly consists of a hybrid populated with four LBIC [9]–CDP [10] chipsets, which are bonded to the detector via three pitch adaptors as illustrated schematically in Fig. 1. These electronics were suitable and available for the detector measurements and operate at the full ATLAS clock frequency of 40 MHz. They are not, however, designed for use within the ATLAS experiment, and some components are not radiation-hard.

The LBIC is an analogue chip with a 22 ns shaping time, performing preamplification, shaping and discrimination of the signal from the detector strips. Each LBIC reads 64 strips and compares the charge on each with a single, definable threshold which is common to all the channels. The corresponding 64 output channels are set either high or low to indicate a strip being above or below the

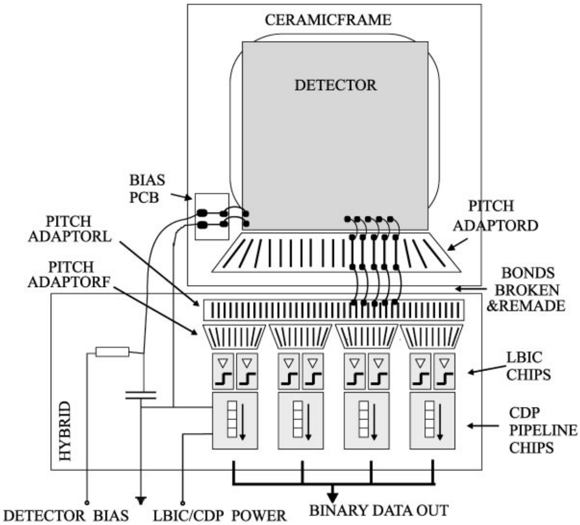

Fig. 1. Schematic showing a detector bonded to the binary readout chips on a hybrid via 3 pitch adaptors.

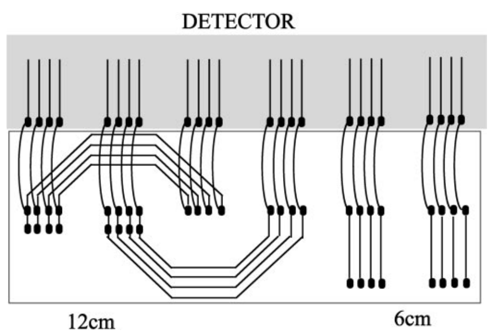

Fig. 2. Schematic detailing the detector bonding to pitch adaptor D, showing the bussing to allow the readout of 6 and 12 cm long strips.

threshold. The 128 output channels from two LBICs are bonded to one CDP chip, which places the hitmap into a pipeline clocked at 40 MHz. The pitch adaptor 'D' of Fig. 1 incorporates bussing which allows for two of the chipsets to be bonded to 6 cm long detector strips and the other two chipsets to be bonded to effectively 12 cm long detector strips as illustrated schematically in Fig. 2. The minimum separation of two strips connected to the same readout channel is 32 strips, or 2.56 mm. Pitch adaptor 'L' of Fig. 1 consists of long wide metal pads at 100 μm pitch to allow for the repeated bonding and unbonding of the readout electronics to the detectors.

The thresholds applied to the LBIC discriminators were calibrated in terms of equivalent input charge for each of the six readout assemblies. Results are presented for 1 fC threshold, which is the one specified for the ATLAS SCT detector readout (the most probable charge created by a minimum ionising particle traversing a 300 μm thick silicon detector at normal incidence is 3.5 fC). The design goal of the ATLAS experiment is to limit the channel occupancy due to noise to the level of 5×10^{-4}, which requires the discrimination level in the front-end electronics to be set to 3.3 times the r.m.s. noise value [1].

5. Test beam data

5.1. The test beam set-up

The detector assemblies under test were installed in the CERN SPS H8 beamline. The layout of the experimental set-up is shown schematically in Fig. 3. The beam consisted of pions of momentum 180 GeV/c and had transverse size approximately 15×15 mm^2. Four detector planes, referred to as telescope modules, were used to track the beam particles. These telescope modules were made from silicon strip detectors with 50 μm pitch connected to slow analogue electronics. They allowed the beam track trajectories to be projected to the detector assemblies under test with an accuracy of around 2 μm [8] in both the horizontal and vertical planes if there were hits in all four telescope modules, or at worst around 4 μm if there were only hits in one of the upstream and one of the downstream modules. The detector assemblies under test were mounted in-line in a light tight box and maintained at a temperature of around -10°C in a dry nitrogen atmosphere. They were aligned so that the centre of the beam spot coincided approximately with the boundary between adjacent 6 and 12 cm regions, thus allowing the testing of both.

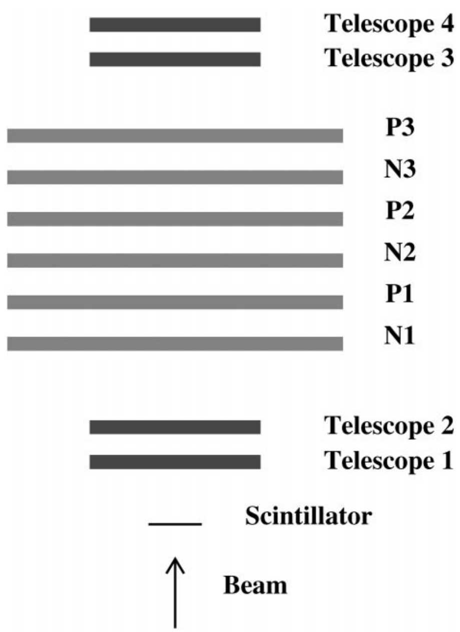

Fig. 3. Schematic layout of the beam telescope and detector assemblies N1–N3, P1–P3 in the CERN H8 beam-line.

5.2. The test beam analysis

The data were analysed to determine, as a function of detector bias voltage, the efficiency, resolution and hit cluster size of each of the six irradiated detectors under test. The beam telescope was used to reconstruct the pion trajectory, which was then projected to the planes of the individual detector assemblies. For each event, this interpolated beam track position was compared with the position of hits in the detector. The detector assembly was classed as efficient if it contained a hit within ± 160 μm of the projected beam track intersect. This cut was large enough to accommodate small changes in software alignment between data-taking runs. Any hits beyond ± 200 μm of the intersect were classed as noise hits. Hits in channels identified as bad were not used in the analysis, and events in which the track intersect was found to cross the detector within ± 160 μm of a bad channel were discarded for that assembly. For the purpose of this analysis, a channel was defined to be bad if its noise-occupancy (the fraction of events for which the noise of that channel exceeded the threshold) was either four times larger or smaller than the average of its neighbouring channels.

To avoid ambiguity, events having more than one reconstructed beam telescope track were discarded from the analysis. However, due to telescope plane inefficiencies, only two telescope hits (one upstream and one downstream of the detector assemblies, see Fig. 3) were required to define a beam particle, and this resulted in some fake reconstructed tracks. To eliminate these, tracks were verified by requiring that two detector assemblies, excluding the one under test, had hits associated with the reconstructed track.

5.3. The test beam results

Results are presented for the 6 cm regions of the six irradiated detectors; the data from the 12 cm regions display the same features and trends. Very similar noise values have been measured for all the detectors, and a noise-occupancy rate of approximately 3×10^{-4} is found for the 6 cm long strips at a single-strip binary readout threshold of 1 fC.

5.3.1. Efficiency versus bias voltage

The measured variation of efficiency with detector bias voltage at a single-strip binary readout threshold of 1 fC is shown in Fig. 4 for the three p-in-n irradiated detectors and in Fig. 5 for the n-in-n detectors.

As expected from previous results [2–4], the n-in-n detectors maintain high efficiency at low bias voltages. The full depletion voltages of these different 300 μm thick n-in-n detectors, as determined by capacitance–voltage (C–V) measurements at 100 Hz [6], were in the range 300 – 380 V at the time of the test-beam measurement. We have found that such C–V full depletion voltages for irradiated n-in-n detectors agree well with the voltage at the onset of the plateau in charge collection efficiency as measured in the laboratory with a detector coupled to a FELIX analogue chip [11] and exposed to a Ru^{106} β-source. The results of Fig. 5 thus show that, for particles at normal incidence, all three irradiated n-in-n detectors are maintaining high efficiency for bias voltages down to around half-full depletion.

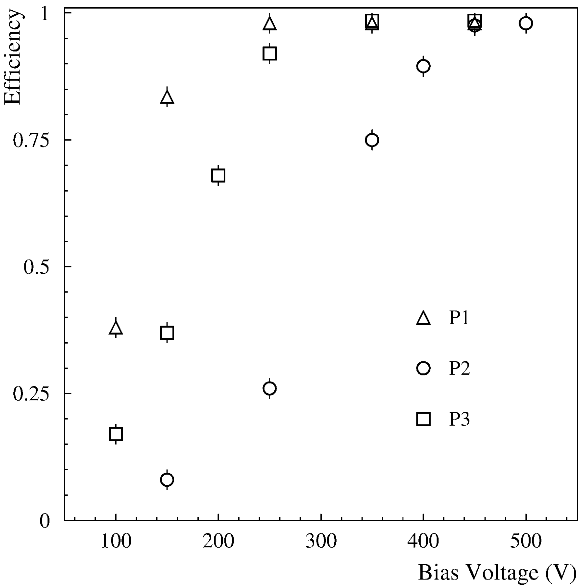

Fig. 4. Measured efficiency as a function of bias voltage at a single-strip binary readout threshold of 1fC for the three irradiated p-in-n detectors, P1–P3.

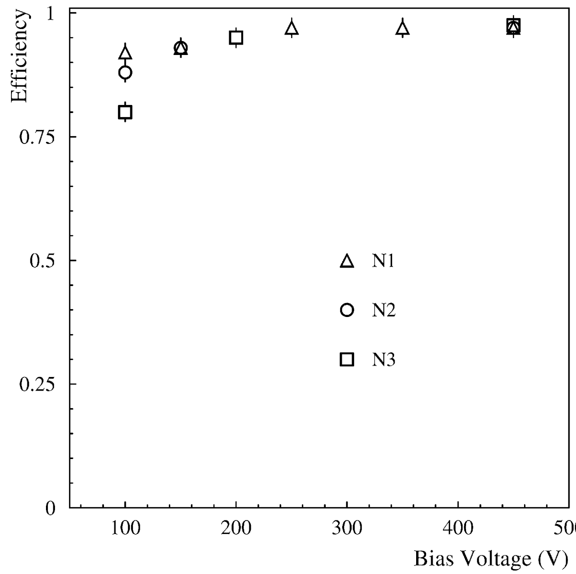

Fig. 5. Measured efficiency as a function of bias voltage at a single-strip binary readout threshold of 1fC for the three irradiated n-in-n detectors, N1–N3.

In contrast, wide variations are seen in the plots of efficiency versus bias voltage for the three p-in-n detectors, Fig. 4. However, allowance must be made for the different detector thicknesses listed in Table 1. Scaling the value of the bias voltage for the onset of full efficiency to an equivalent 300 μm thick detector gives a similar result of approximately 350 V for detectors P2 and P3. Detector P1, however, shows the onset of full efficiency for normally incident particles at around 200 V bias. Such a difference is also found in the full depletion voltages determined from C–V measurement at 100 Hz [6], where for P1 a value of around 150 V is observed, in contrast to the values of over 300 V for P2 and P3 (when normalised to 300 μm thickness).

It is interesting to note that, for these irradiated p-in-n detectors, the bias voltage required for the onset of the maximum charge collection efficiency as determined with analogue readout is greater than the full depletion voltage coming from C–V measurement at 100 Hz. This is illustrated in Figs. 6 and 7 for detector P1. In Fig. 6 it is seen that the measured charge collection efficiency saturates at about 300 V bias, while Fig. 7 shows that full depletion from the C–V measurement at 100 Hz is at around 150 V.

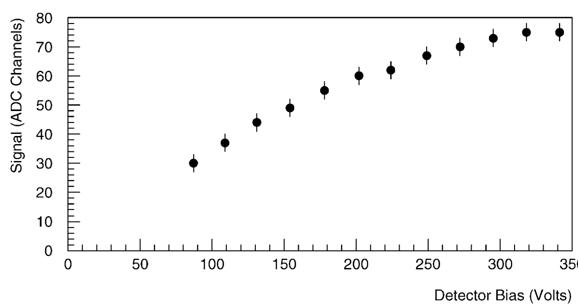

Fig. 6. Relative charge collection efficiency measured as a function of bias voltage for the irradiated detector P1. The detector was exposed to a Ru^{106} β-source and read out with a FELIX analogue chip [11].

No obvious reason has been found for the lower depletion voltage of detector P1. It is manufactured from standard silicon substrate material, as used also for detector N1. A large spread in depletion voltage has previously been observed with different

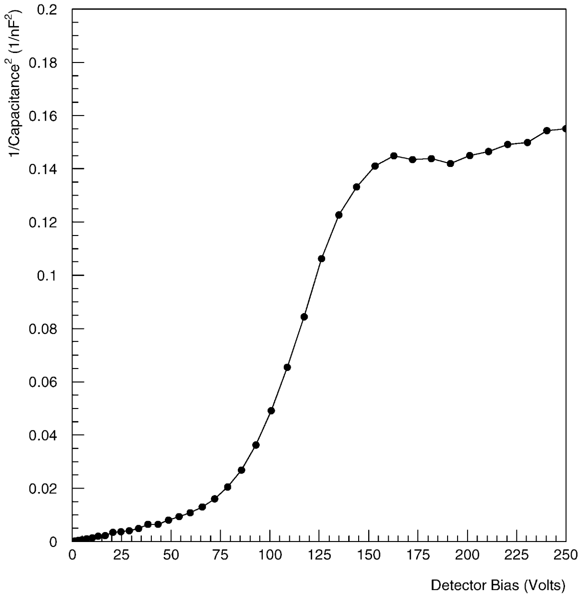

Fig. 7. Plot of 1/Capacitance^2 versus bias voltage for the irradiated detector P1. The capacitance measurement was made at a frequency of 100 Hz.

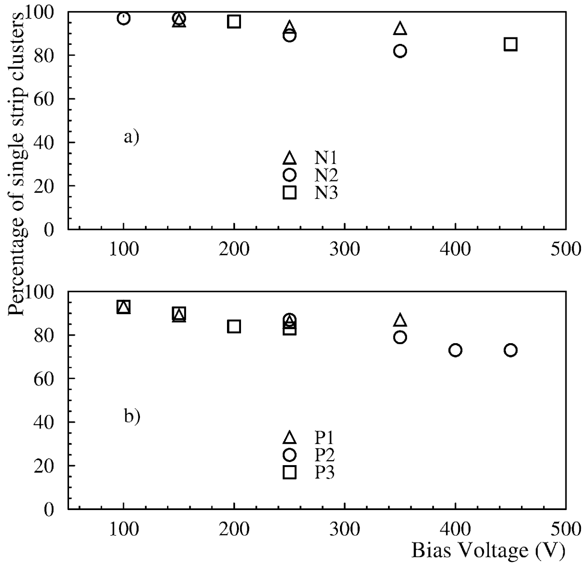

Fig. 8. Percentage of single-strip matched clusters as a function of bias voltage at a single-strip binary readout threshold of 1 fC (a) for the irradiated n-in-n detectors and (b) for the irradiated p-in-n detectors.

irradiated diodes [12]. It appears that, whereas detector bulk leakage current can be closely predicted following irradiation, depletion voltage is not a well controlled parameter.

The results of Fig. 4 support the expectation that the irradiated p-in-n detectors have to be operated close to their full depletion voltage, or above, for full efficiency following type-inversion. The efficiency falls rapidly with voltage below this point.

5.3.2. Detector resolution and strip readout cluster size

Contiguous detector strips giving signals above the 1 fC single-strip binary threshold are combined together to form a cluster, with the hit position determined from the average coordinate of the strips in the cluster. For high efficiency with single-strip threshold binary electronics it is desirable to have most charge collected on only one strip, and hence most clusters to be single-strip. The detectors are designed to minimise charge sharing between adjacent strips [1].

The percentage of single-strip clusters in the hits matched to the beam tracks are shown in Figs. 8(a) and (b) for the n-in-n and p-in-n detectors as a function of bias voltage. The binary threshold is again 1 fC and the tracks are at normal incidence to the detectors. As expected for a fixed threshold, the cluster size increases as more charge is collected on the strips. However, for both n-in-n and p-in-n detectors of 300 μm thickness, the percentage of single strip clusters is high for tracks at normal incidence, in excess of 80% at voltages necessary for efficient operation.

The measured detector resolutions as a function of bias voltage are shown in Figs. 9(a) and (b) for the n-in-n and p-in-n detectors. The values for all detectors are close to $1/\sqrt{12}$ of the detector strip pitch (that is, 23 μm), as expected for the predominantly single-strip clusters. An example of the distribution of track residuals is shown in Fig. 10 for detector P1 at 350 V bias. The only significant variations seen in the resolutions of Figs. 9(a) and (b) are for p-in-n detectors operated at bias voltages such that their efficiency is very low; P2 at 250 V and P3 at 100 V. Here the poor measured

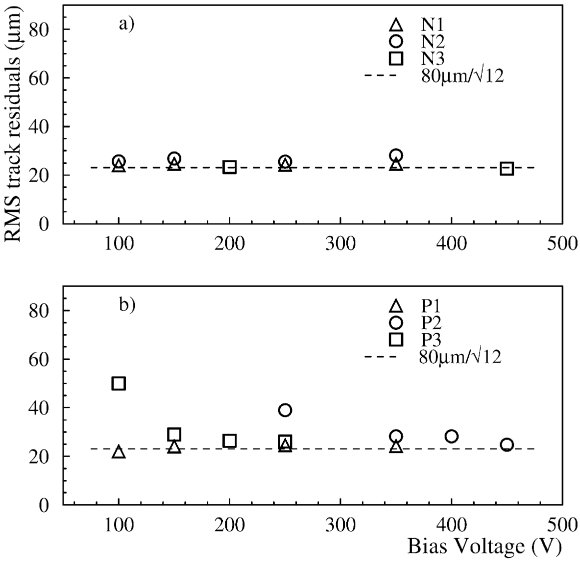

Fig. 9. RMS residuals of matched hit coordinates from the interpolated beam track position as a function of bias voltage (a) for the irradiated n-in-n detectors and (b) for the irradiated p-in-n detectors.

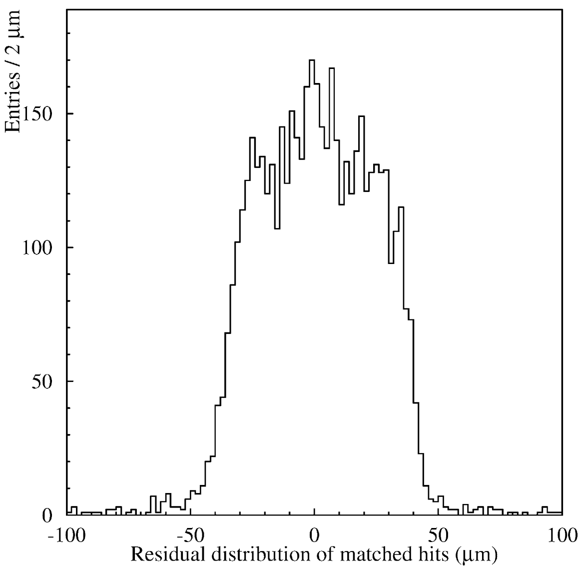

Fig. 10. Distribution of the residual of the matched hit coordinate from the interpolated beam track position for irradiated detector P1 at 350 V bias.

resolution provides evidence for the spreading of induced charge at the strips in irradiated p-in-n detectors operated below depletion.

6. Strip quality of irradiated detectors

Any loss of good detector readout strips during irradition needs to be quantified for all candidate prototype detectors produced for an experiment such as ATLAS. For n-in-n detectors, high-field regions at the p-stop isolation implants following type inversion may result in excessive noise due to micro-discharge [13]. In addition, for both n-in-n and p-in-n detectors with AC capacitively coupled readout through grounded metal strips, the coupling dielectric is vulnerable to punchthrough if high currents induced by beam spills cause a significant fraction of the bias voltage to be applied briefly across this dielectric instead of the detector bulk.

The strip quality in respect of the percentage of strips having shorts through the AC-coupling dielectric induced during detector fabrication or irradiation, or anomolies in readout noise values arising from radiation induced effects such as microdischarge, have been measured for detectors P1, N3 and five detectors of type N2. Results for the n-in-n detectors are described fully in Ref. [14]. The individual strips were probed to check for shorts in the AC-coupling dielectric caused by irradiation. In addition, the noise on each strip was measured with the detector attached to the binary readout scheme described in Section 4. An example of the noise on 128 channels of the first 12 cm readout region of detector P1 is shown in Fig. 11. For this measurement the detector was biased at 300 V and maintained at a temperature of $-12°C$. The non-functioning readout channel numbered 242 seen in Fig. 11 is due to a fault on the hybrid, whereas the five channels with slightly higher noise

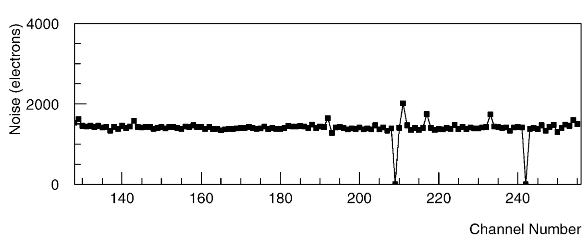

Fig. 11. Plot of noise (in electrons) versus channel number for 128 channels of 12 cm strip readout of the irradiated detector P1 at 300 V bias and a temperature of $-12°C$.

and the saturated channel numbered 209 all have shorts in the AC-coupling dielectric. The absolute noise level of about 1500 ENC is as anticipated for such an irradiated detector with LBIC-CDP fast readout [1].

Each of the detectors P1 (p-in-n) and N3 (n-in-n) was found to have in total approximately 1% bad channels (dielectric shorts plus noisy channels) after the irradiation, about half of which were induced by the irradiation process. This figure matches the specified requirement of the ATLAS SCT [1]. The N3 detector was designed to reduce the field values at the p-stop isolation implants by use of a novel polysilicon field plate isolation technique [7]. In contrast, the five detectors of type N2, made by the same manufacturer but with conventional individual p-stop isolation, all showed regions of excessive noise following the onset of micro-discharge [14]. This led to there being approximately 7% bad strips for each of the N2-type detectors after irradiation, measured at 300 V bias. A strip isolation design of the type N3, rather than N2, is therefore appropriate with this manufacturer for n-in-n detectors that are to be irradiated beyond type inversion.

7. Summary

A sample of full-sized p-in-n and n-in-n silicon microstrip detectors prototyped to the ATLAS design and coming from four different manufacturers has been tested after irradiation at the CERN PS to a fluence of 3×10^{14} p cm^{-2} 24 GeV/c protons. Test beam and strip quality measurements show good post-irradiation performance for both the p-in-n and n-in-n detectors when read out with fast single-strip threshold binary electronics. As anticipated, the irradiated n-in-n detectors are still efficient at voltages as low as half-full depletion with a 1 fC binary threshold, whereas the p-in-n detectors need to be fully depleted for high efficiency, and operated at still greater voltages to achieve full charge collection efficiency. A large spread in post-irradiation depletion voltages is observed for the p-in-n detectors tested.

Following the satisfactory performance illustrated by these results, p-in-n silicon microstrip detectors with AC capacitively coupled readout were chosen for the ATLAS SemiConductor Tracker. An extensive programme was initiated to prototype and evaluate significant numbers of such detectors from a range of manufacturers in preparation for the procurement phase of the experiment.

Acknowledgements

We acknowledge with pleasure the invaluable technical support for this work provided in our institutions; in particular, B. Fromant at Cambridge University, R. Boulter, R. Fortin and J. Godlewski at CERN, P. Turner and M. Wormald at Liverpool University, J. Bizzell at the Rutherford Appleton Laboratory and C. Grigson and R. Nicholson at Sheffield University. We also thank the PS and SPS staff at CERN for the efficient operation of these accelerators during our measurements, and colleagues within ATLAS for their help in the detector irradiation and the test beam data taking. We thank the following funding agencies for support: the UK Particle Physics and Astronomy Research Council, the Japan Ministry of Education, Science and Culture, the Japan Society for Promotion of Science, the Australian Research Council (ARC) and the Australian Department of Industry, Science and Resources (DISR), AEN97-1712-C02-01, CICYT, Spain.

References

[1] ATLAS Inner Detector Technical Design Report, CERN/LHCC/97-16, ATLAS TDR 4 (1997). (http://atlasinfo.cern.ch/Atlas/GROUPS/INNER_DETECTOR/TDR/tdr.html).
[2] T. Dubbs et al., Nucl. Instr. and Meth. A 383 (1996) 174.
[3] F. Albiol et al., Nucl. Instr. and Meth. A 409 (1998) 236.
[4] P.P. Allport et al., Update on Progress with ATLAS Full-sized Prototype Detectors, presented at the Third International Symposium on Development and Application of Semiconductor Tracking Detectors, Melbourne, 1997, (http://hep.ph.liv.ac.uk/ ~ allport/).
[5] L. Andricek et al., Radiation hard single sided P + N detectors optimized for single threshold binary readout, Presented at the Third International Symposium on Development and Application of Semiconductor Tracking

Detectors, Melbourne, 1997 (http://www.hll.mpe-garching.mpg.de/~ lca/).

[6] D. Morgan et al., Nucl. Instr. and Meth. A. 426 (1999) 366.

[7] Y. Unno et al., Novel p-stop structure for n-strip readout detector, Presented at the Third International Symposium on Development and Application of Semiconductor Tracking Detectors, Melbourne, 1997 (http://arkhp1.kek.jp:80/ ~ unno/notes.html#Conference).

[8] J. Beringer et al., Nucl. Instr. and Meth. A 383 (1996) 205.

[9] E. Spencer et al., IEEE Trans. Nucl. Sci. NS- 42 (1995) 796.

[10] J. DeWitt, A pipeline and bus interface chip for silicon strip detector read-out, Proceedings of the IEEE Nuclear Science Symposium, San Francisco, CA, USA November 1993.

[11] S. Gadomski, P. Weilhammer, Nucl. Instr. and Meth. A 351 (1994) 201.

[12] RD2 Collaboration, Final Report on the RD2 Project, CERN/LHCC/96-5 (1996).

[13] T. Oshugi et al., Nucl. Instr. and Meth. A 383 (1996) 166.

[14] D. Robinson et al., Nucl. Instr. and Meth. A 426 (1999) 28.