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Radiation hard strip detectors for large-scale silicon trackers

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Abstract

Major challenges in building silicon strip detectors for future high luminosity experiments are the high radiation level and the huge number of sensors required for the construction of the precision layers of the complete tracking system. Single-sided p^+n strip detectors for ATLAS SCT designed and fabricated at the MPI Semiconductor Laboratory have been exposed to $3\times10^{14}/cm^2$ 24 GeV protons. The major features of the design, including the biasing technique using implanted resistors, are discussed and results are presented. The technology was transferred to CiS, Germany, a company capable of the desired large-scale production. Results of this industrially fabricated sensors look very promising and show the expected radiation hardness.

Keywords: Silicon detectors; Radiation hardness; Implanted resistors

1. Introduction

The detectors to be described in this paper have been developed at the MPI Semiconductor Laboratory for use in the ATLAS experiment at the LHC. The Semiconductor Laboratory is involved in the device and process development for the strip detectors of the SemiConductor Tracker (SCT) and the pixel detectors in the inner layers as well. Concept and design are based on earlier experience with double-sided detectors [1] and extensive device simulations [8]. The p^+n option (p-type strips on n-type substrate) for the strip detectors has been chosen for reasons of simplicity of the production method. Simultaneously, the lower electrical field strengths make these devices less prone to electrical breakdown.

The large number of sensors needed in ATLAS has to be produced in industry and in order to achieve a high yield at low production cost the design as well as the process technology has to be fault tolerant and cost effective. The use of implanted bias resistors in these detectors leads to considerable simplification in the technology compared to the widely used polysilicon resistors.

Exposing detectors to the radiation environment at LHC will induce bulk defects with concentrations exceeding by far those of the original dopants. In addition, oxide and Si–SiO_2 interface damage leads to an order of magnitude increase of the oxide charge resulting in locally enhanced electric field strengths and possibly to electric impact ionisation

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and breakthrough. The well-known consequences of the bulk material changes [2] are an increase of detector leakage current, the change of effective doping from n- to p-type (type inversion) followed by a steady increase of full depletion voltage, and signal loss due to enhanced charge trapping after radiation damage. Less well known is the low conductivity of the undepleted bulk material found experimentally [3–5] and which can be explained by the creation of near mid gap acceptor type defects [6]. It gives a key for understanding the survival of single-sided p^+n detectors after type inversion. The detectors designed for LHC operation will have to function properly despite the drastic radiation-induced material property changes, in particular, it should be possible to operate them at the high depletion voltage with reasonable power consumption.

Double- and single-sided strip detectors fabricated at the MPI Semiconductor Laboratory have been tested before and after irradiation with protons in the ATLAS irradiation program. For large-scale production the technology was transferred to the CiS, Erfurt, Germany. Full size single-sided p^+n ATLAS strip detectors have been fabricated by this company. Subsequent tests show that those detectors have the expected excellent radiation hardness.

2. Detector design and static measurements

2.1. Concept

The basic design features, including the edge region and the properties of the p^+n detectors after type inversion, are described already in Ref. [7]. Prototyping and technology development is done on 280 μm thick wafers with a bulk resistance of 2–3 kΩ cm. The sensors have the ATLAS barrel topology, i.e., they have a sensitive region of 62×61.6 mm^2 with 80 μm readout pitch. The sensors fabricated at CiS are designed for the ATLAS Forward Region on 2–5 kΩ cm material and 300 μm thickness. These are wedge-shaped sensors with an area of roughly 36 cm^2 and a varying pitch from 70–90 μm.

2.2. Biasing method

The decision to use p^+n detectors in ATLAS opens the possibility to introduce implanted resistors for the biasing of the capacitively coupled devices instead of polysilicon resistors. Polysilicon resistors have been used for many years to implement the required high resistance values on the detectors. For the new LHC experiments where the signal formation time of the electronics is around 20 ns there is no need to have that high resistance values. In Fig. 1 the total noise of the readout system as a function of the bias resistance is shown. The thermal noise of the bias resistor, $ENC_{th} \approx (1/q)\sqrt{4kT\tau/R}$, is added in quadrature to the initial noise levels ENC_0 which are mainly dominated by the R/O electronics with the capacitive load of 12 cm long readout strips. It demonstrates that a resistor value of about 100 kΩ already adds almost negligible noise when using the fast ATLAS R/O electronics.

The implanted resistor is formed by a medium-dose boron implantation and needs only one photolithographic step. This is considerably less than the number necessary for the production of polysilicon resistors. This advantage offers not only cost saving for production but also the absence of small size contacts between different materials (metal–poly and metal–silicon or poly–silicon) leads to a higher yield and decreases the testing effort compared to the polysilicon technology (Fig. 2).

2.2.1. Uniformity before irradiation

The choice of the implantation dose is driven by the radiation-induced changes in the oxide. The negative boron acceptor charge will be partially compensated by the radiation-induced positive oxide charge resulting in an increasing bias resistance with irradiation. However, as long as the resistor channel is not pinched off completely an increasing bias resistance does not affect the detector performance. To avoid pinch off, the chosen implanted acceptor dose is substantially higher than the expected oxide saturation dose of a few 10^{12} cm^{-2}. For the CiS detectors a boron implantation with 120 keV and a dose 1.4×10^{13}/cm^2 was used. The

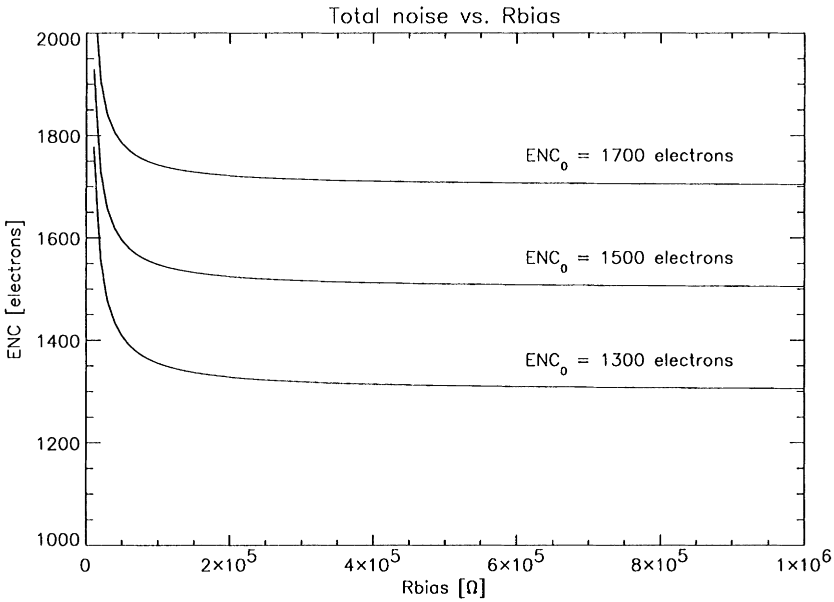


Fig. 1. Contribution of the bias resistor to the total noise for three different initial noise levels. The total noise is shown as a function of the bias resistance. A signal formation time of 25 ns was assumed.

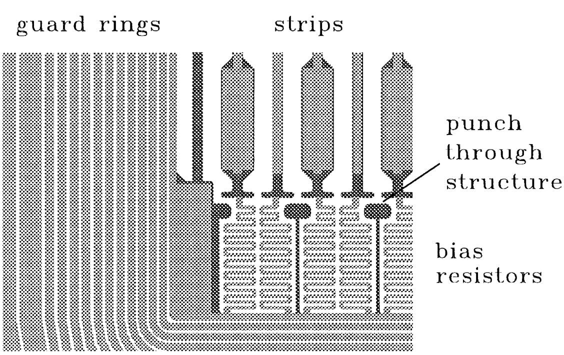


Fig. 2. Closeup of the detector edge region including strip bias resistors and multiguard edge protection structure. The punch-through structure operating in parallel to the resistor limits the voltage drop across the resistor in case of irradiation bursts.

effective acceptor dose in the silicon of $10^{13}/cm^2$ results in a calculated sheet resistance of 2.9 kΩ/sq.

The uniformity of the implanted bias resistors over the wafer is shown in Fig. 3. Every second resistor was tested and minimal variation over the full width was found. The occupied area for the meander-type implantation was $140 \times 90\ \mu m^2$ and the measured sheet resistance 3.1 kΩ/sq before irradiation. The uniformity over a batch was tested on 1 cm^2 small "baby"-detectors from 11 wafers. The results are shown in Fig. 4. The mean values of the individual wafers are plotted.

2.2.2. *Safety feature*

The layout of the biasing region in Fig. 2 shows another interesting feature. There is a punch-through structure in parallel to the bias resistor. In normal operation mode the voltage drop over the bias resistor is too small to turn on the punch through between bias line and strip. But in the case of a sudden radiation burst the resulting high strip current is sinked by this punch-through structure instead of the bias resistor. The measurement result in Fig. 5 shows that the onset of the parallel punch-through structure is around 20 V. A high current of around 0.2 mA due to a sudden radiation burst results in a voltage drop between strip metal and implant of only 23 V. The voltage drop along the strip implantation is neglected in this measurement.

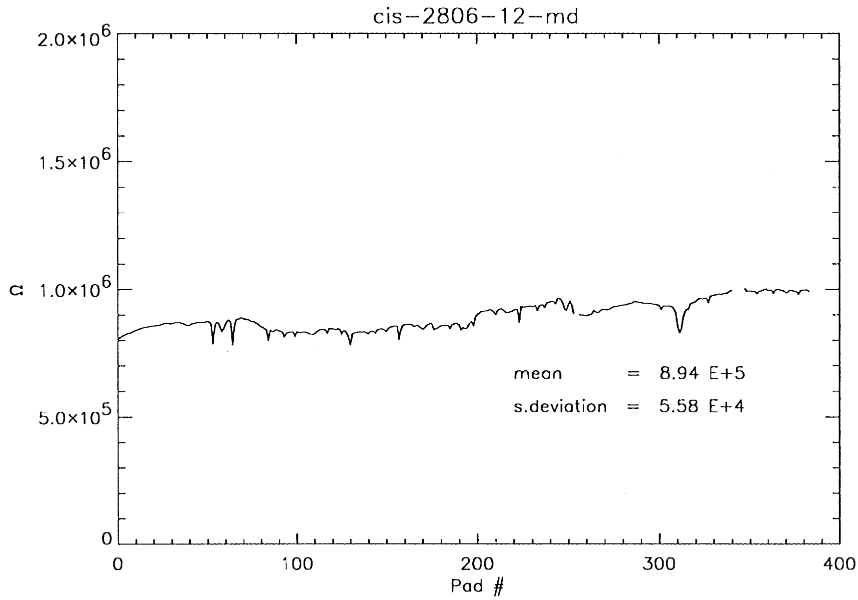


Fig. 3. Resistance variation across prototype detector CiS 2806-12. Every second out of 768 meander-type resistors was measured on the probe station.

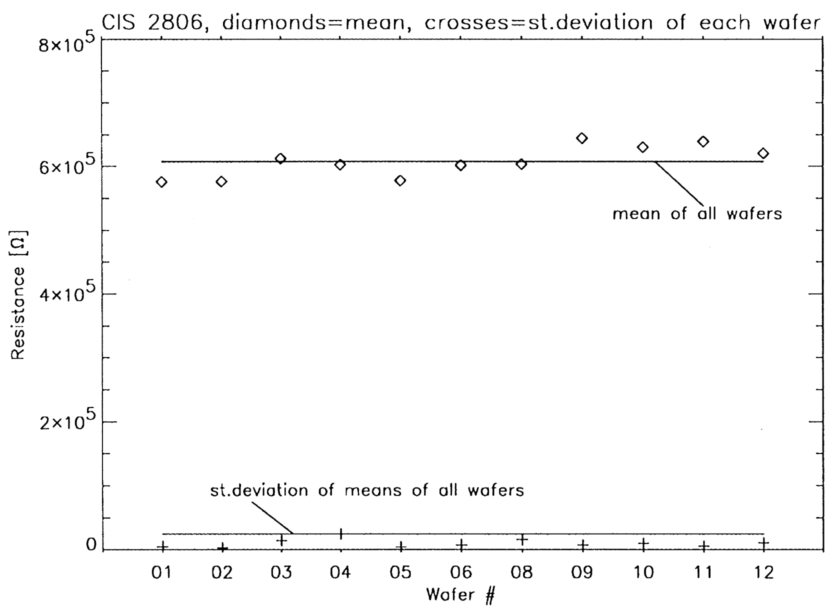
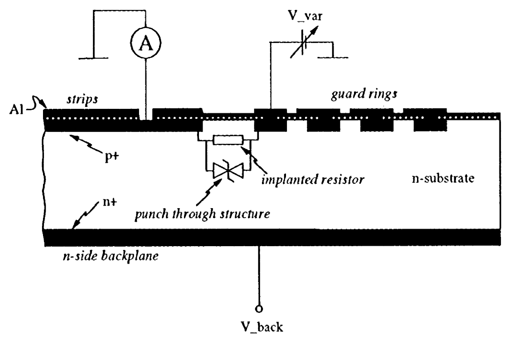


Fig. 4. Summary of test detector measurements on CiS batch 2806.

2.2.3. Irradiation of the implanted resistors

Test structures with implanted resistors processed at CiS were irradiated with X-rays from a tungsten target (energy continuum with a peak at around 10 keV). The irradiation was carried out on an X-ray irradiation facility at CERN. Five test structures of one batch, each of them with five resistors of linear shape, were measured after



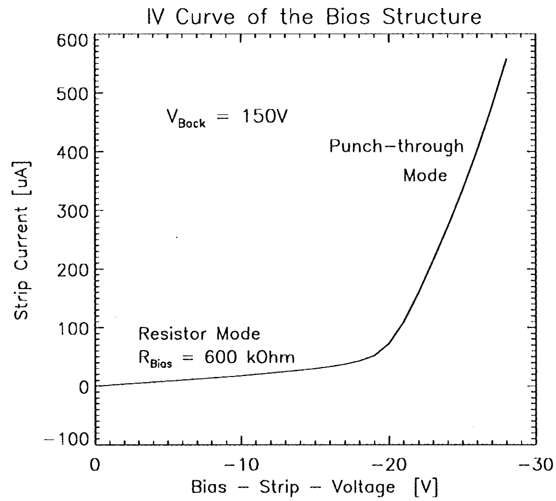


Fig. 5. Principle of the safety feature against radiation bursts.

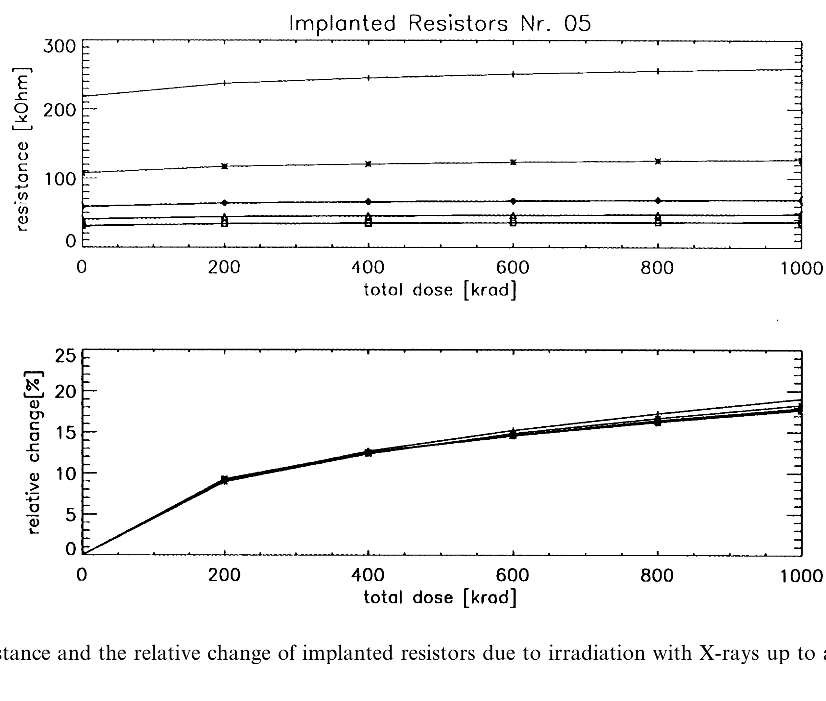


Fig. 6. Total resistance and the relative change of implanted resistors due to irradiation with X-rays up to a dose of 1 Mrad.

different doses up to 1 Mrad. According to the different aspect ratios the total resistance varies between 30 and 220 kΩ. The resistors were not biased during the irradiation and the resistance was measured by applying 1 V over the resistor and recording the current. The I–V characteristics in the range between − 1 and + 1 V had a perfectly linear behaviour both before and after irradiation. Fig. 6 shows the result for one structure. As expected the resistance increased after irradiation due to the higher concentration of oxide charges. All of the devices had a similar behaviour and the relative

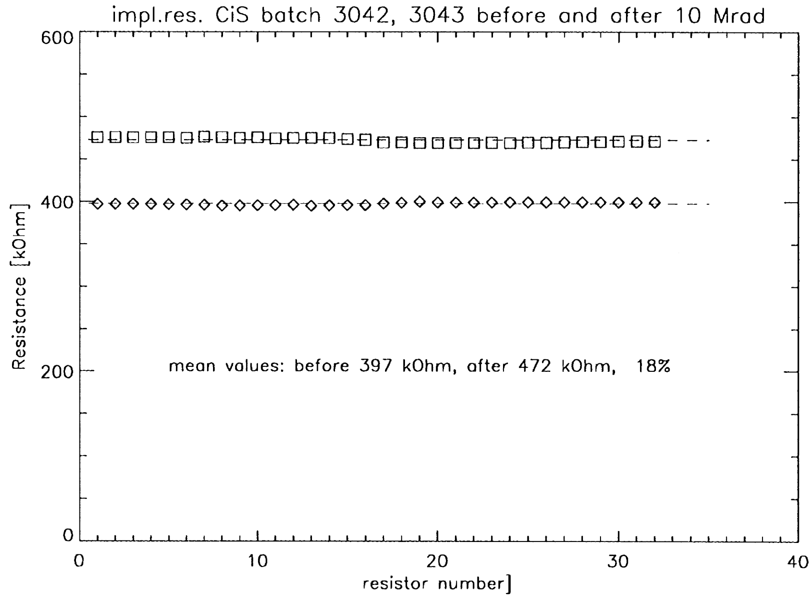


Fig. 7. After 10 Mrad X-ray irradiation the mean resistance value of 32 tested resistors increased by 18%.

change of the resistance is in the range between 15% and 24% for all of the various resistors. The mean relative change of all the resistors was 18.7% after 1 Mrad. 32 meander-type resistors from two other CiS batches with the same implantation dose and energy were tested separately up to a dose of 10 Mrad, the expected dose after 10 years LHC operation. The mean value of the resistance increased by 18% (Fig. 7).

3. Detector characteristics after irradiation

In September 1997 two detectors fabricated at the MPI Semiconductor Laboratory were irradiated up to 3×10^{14} cm^{-2} 24 GeV/c protons at the CERN PS. The detectors were biased at 150 V during the irradiation and kept cold at -7°C. Subsequent controlled annealing for 21 days at 25°C [9] simulates the yearly warm-up of 2 days at 20°C and 14 days at 17°C during 10 years LHC operation in ATLAS [10]. In 1998, eight detectors made by CiS using the same technology were irradiated up to the same dose. They were biased at 100 V during irradiation and six of them have been annealed during 6 days at 25°C. The following sections will describe the characteristics of the MPI and CiS detectors after irradiation.

3.1. Static measurements after irradiation

The I–V curves of the MPI detectors were taken inside a temperature cabinet at various temperatures (Fig. 8). The electronics was biased during the measurement and the strips with no readout were held on ground potential by bonding them via a pitch adapter to ground. The current at 500 V versus the temperature shows an exponential behaviour. But a fit to the curve gives a characteristic energy of 1.26 eV (instead of 1.13 eV band gap at this temperature). This behaviour can be understood if one assumes a higher density of traps close to the midgap energy [11]. The exponential temperature dependence indicates that there is no additional current contribution besides the expected generation-recombination current.

The currents were normalised to 0°C using the standard temperature dependence with the characteristic energy of 1.26 eV. The power density versus the operating voltage in Fig. 9 shows a linear

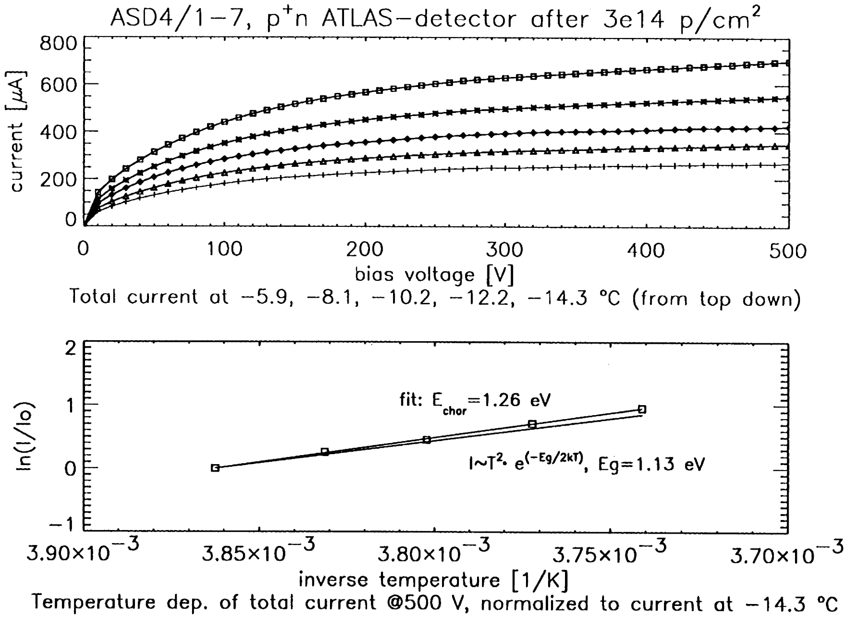


Fig. 8. I–V characteristics after irradiation and annealing taken at various temperatures.

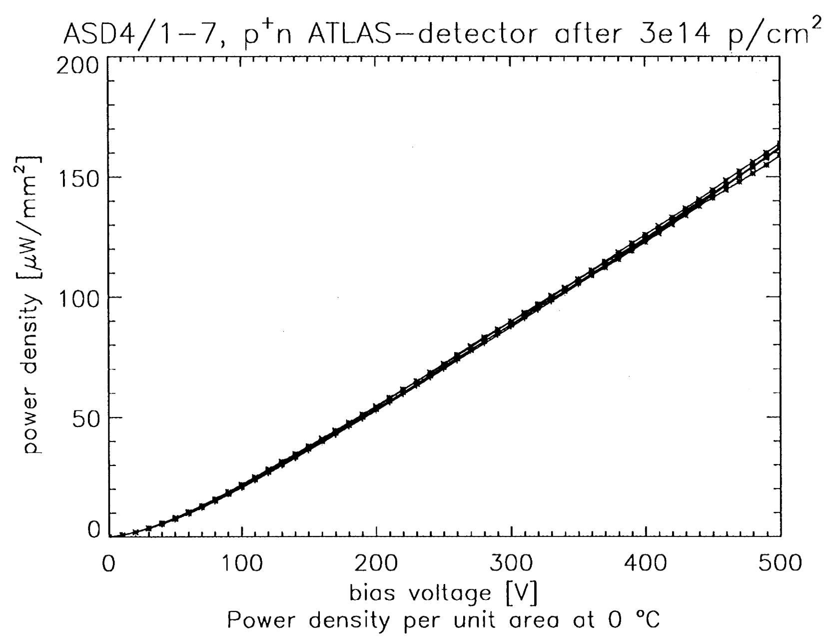


Fig. 9. Power density of the irradiated detector measured at various temperatures and normalised to 0°C.

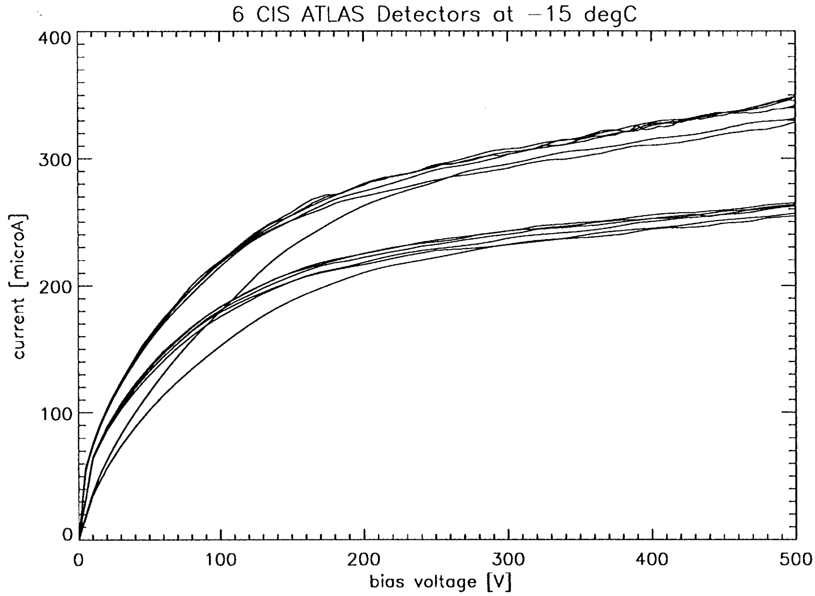


Fig. 10. I–V curves of six irradiated CiS ATLAS detectors before (upper current level) and after (lower level) annealing of 6 days at 25°C. Measurement was done at − 15°C.

behaviour above a few tens of volt and is roughly 100 μW/mm^2 at 0°C and 350 V, the maximum operating voltage foreseen in ATLAS. The I–V curves of the six annealed CiS detectors are very similar (Fig. 10). The detectors have a very homogeneous current level at higher voltages. Also, the temperature dependence of the current is exponential like for the detectors fabricated at MPI Semiconductor Laboratory.

3.2. Signal and noise measurements

Signal and noise properties were investigated with unirradiated FELIX electronics [12] which was bonded to the detectors after the end of irradiation. This electronics has an intrinsic risetime of approximately 75 ns and a built-in feature of signal processing (deconvolution) making it possible to use effectively 25 ns shaping. Strips were connected in such a way as to study the situation with 6 cm long strips corresponding to the use of a single detector and 12 cm length corresponding to daisy-chained detectors as foreseen for ATLAS modules. Signal measurements were performed with a ^{90}Sr beta source.

The signals are reconstructed forming a cluster consisting of the total charge in a maximum of five consecutive strips. Such a cluster is initiated by a seed of a strip with 4σ signal and accepted when it has a total charge of at least 5σ above the average noise of the particular channels. A Landau distribution (convoluted with a Gaussian) is fitted to the obtained pulse height spectrum.

Signal and noise spectra obtained in "peak mode" corresponding to 75 ns shaping are shown as function of the bias voltage in Fig. 11 on the left-hand side. Full signal height on the annealed detector is reached at 400 V, measurements extend up to 600 V. The S/N ratio in the saturation region is 16 for the 12 cm region. Notice that the noise does not increase with overdepletion of the detector. Essentially the same properties are found with 25 ns effective shaping (deconvoluted mode). The corresponding S/N ratio with the ATLAS relevant peaking time is 12 for 12 cm long strips (Fig. 11, right side). The same measurements have been performed with a detector made by CiS, shown in Fig. 12. Again, there is almost no difference in the results obtained with the MPI detector. The S/N is higher due to the thicker material used

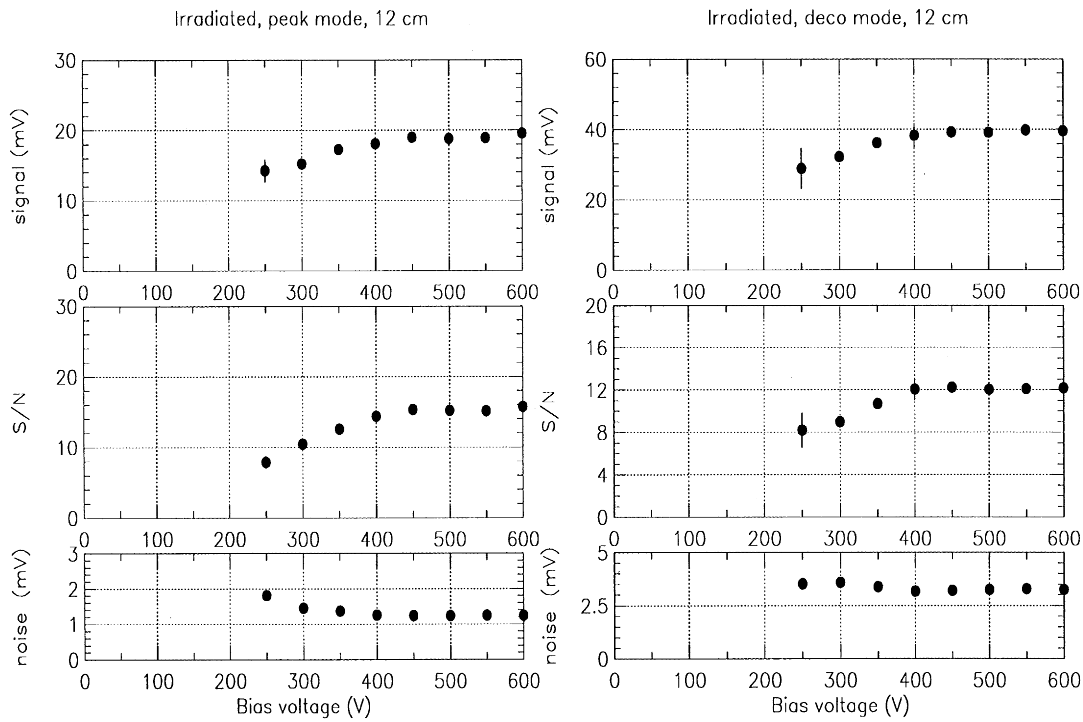


Fig. 11. Signal and noise versus the bias voltage at $-15°C$ of the MPI detector after irradiation in peak (75 ns peaking time) and deconvoluted mode (25 ns peaking time).

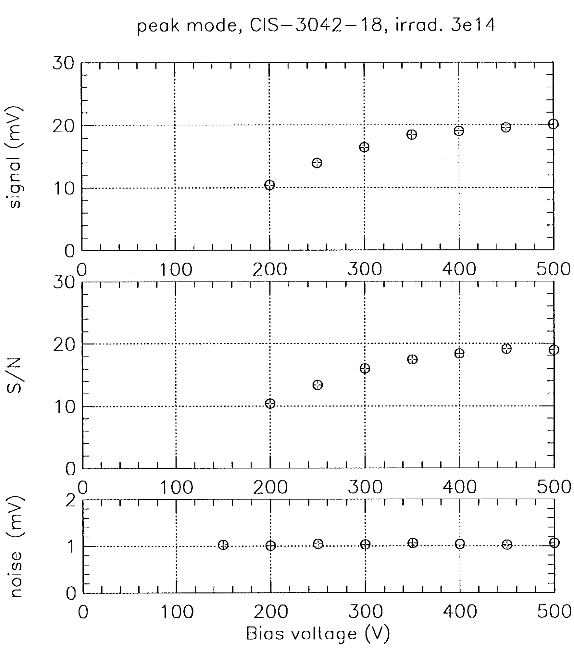


Fig. 12. Signal and noise versus the bias voltage at $-15°C$ of the CiS detector after irradiation.

at CiS and due to the fact that strips on the wedge-shaped CiS detector are shorter. The signal is therefore somewhat higher and the noise lower. It is interesting that the noise of the CiS detector does not increase at lower bias voltages. This is not yet fully understood.

4. Summary and conclusions

Single-sided p^+n detectors for the ATLAS SCT have been developed and built in the semiconductor laboratory of the Max-Planck Institutes in Munich. In their design emphasis was put on radiation tolerance and simplicity of technology in order to allow reliable and cost-effective production. They have been irradiated within the ATLAS irradiation test program to a fluence corresponding to the expected maximum value in the experiment. All tests performed so far indicate that these detectors are adequate for use in the experiment. The developed technology has been successfully transferred to CiS, a company capable of the desired large-scale production for ATLAS SCT. The industrially fabricated sensors show the same excellent properties like the prototypes from MPI.

A feature untried before is the use of implanted bias resistors which can be produced with little technological effort compared with the commonly used polysilicon technology. These resistors perform well in all aspects: reproducibility, radiation resistance and noise properties. Test resistors have been irradiated separately in order to investigate the increase in resistivity after exposure to ionising radiation. After 10 Mrad the increase in resistance was less than 20%.

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