Novel P-stop Structure in the N-side of Silicon Microstrip Detector

Y. Unno[a], T. Kohriki[a], T. Kondo[a], S. Terada[a], M. Numajiri[b], T. Ohsugi[c], Y. Iwata[c], R. Takashima[d], I. Nakano[e], Y. Hayama[f], K. Yamamura[f], K. Yamamoto[f]

[a]Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[b]Radiation Safety Center, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan
[c]Physics department, Hiroshima University, Higashi-Hiroshima 739-8526, Japan
[d]Education department, Kyoto University of Education, Kyoto 612-0863, Japan
[e]Physics department, Okayama University, Okayama 700-8530, Japan
[f]Semiconductor division, Hamamatsu Photonics Co. Ltd., Hamamatsu 435-8558, Japan

Abstract

After identifying the microdischarge location in the n-side, a novel p-stop structure, a p-stop with an extended DC field plate, was invented and implemented in the n-strip readout on the n-bulk Silicon microstrip detector. The detectors showed little increase of leakage current during and after the proton irradiation due to the microdischarge.

I. INTRODUCTION

Silicon microstrip detectors are being used commonly in physics experiments as an apparatus to measure the position of particles passing through the Silicon bulk of the detectors. A large-scale next generation application of the device is the Silicon microstrip detector system in the ATLAS detector at LHC [1].

In order to make the device sensitive, a high voltage is required to deplete the bulk of Silicon, where the depletion starts from the p-n junction side and the depletion voltage is controlled by the impurity concentration. When the detector is placed in the radiation environment of charged particles and neutrons, the effective impurity concentration will change and the initial n-type bulk will invert to p-type after heavy irradiation. The generation of the new impurities are further complicated with the annealing and anti-annealing of the impurities which rates are strongly temperature dependent. In the ATLAS experiment, the Silicon strip detectors, which will experience a maximum fluence of 3×10^{14} particles (1 MeV neutron equivalent)/cm^2, are to be operated at around -7°C to suppress the revelation of the anti-annealing. Including warm-up of the detectors for maintenance, the full depletion voltage is expected to reach about 400 V in the inner-most part of the detectors.

Considering the high depletion voltage and the facts that efficient charge collection is made with the strips in the p-n junction side where the depletion starts and that the reading out from the p-n junction side enables the operation of the detector in a partially depleted mode, the use of Silicon microstrip detector of n-strips on n-bulk has been proposed for the ATLAS detector. The n-strips will become the p-n junction after the type inversion and when the high voltage is required.

In order to make the n-strips-on-the n-bulk detector to work, the n-strips must be isolated resistively and capacitively from the adjacent n-strips. The surface of the Silicon bulk is covered with the Silicon di-oxide (SiO_2) layer for protection, the “passivation” layer. The interface of the oxide and the Silicon bulk will be charged up positively in the fabrication process. This oxide charge attracts the electron carriers in the Silicon bulk and makes the shallow surface of the bulk to be an electron rich layer, being called “accumulation layer”, which is conductive and shorts the n-strips. A common practice is to cut this accumulation layer by implanting a p-type zone surrounding the n-strips, the “p-stop structure”, having the p-n junction on the surface between the n-strips.

The oxide charge is enhanced further due to the ionizing radiation damage. The resistivity of the “accumulation layer” was seen to become very high when the detector was irradiated [2]. An issue has arose whether the resistivity of the accumulation layer is high enough: if it is high enough, the surface potential is governed by the field in the Silicon bulk; if it is not, the surface is more conductive and the potential of the n-strips reaches the boundary of the p-stop without decreasing too much. If the potential of the p-stop is determined by the electric field in the Silicon bulk and the n-strip potential reaches the p-stop, the boundary of the p-stop may generate a high electric field, specially where a defect exists in the boundary.

If the electric field is high enough, it induces the avalanche breakdown. The early stage of avalanche breakdown was identified and called “micro-discharge” [3]. This work has identified the microdischarge in the n-side visually, proposed a novel p-stop structure to prevent the high field associated in the Silicon, and demonstrated that the structure has suppressed the microdischarge in irradiation tests.

II. DC FIELD-PLATE

Identification of “micro-discharge” was first made along the edge of strips with a highly sensitive infra-red camera [3]. The observed phenomenon was global due to a design of the strip detector. Further studies showed that the “micro-discharge” occurred in local spots where the electric field was strong enough, e.g., at the defects in the edge of the strips.

The microdischarge in the edge of the p-strips in the n-bulk Silicon microstrip detector was studied systematically for the AC coupled detector [4]. The situation at the p-strip in the n-bulk is schematically shown in Fig. 1. The readout metal is placed over the p-strip by sandwiching an insulator layer (SiO_2) or layers (SiO_2 + SiN). The p-strip is biased and the highest electric field is around the p-strip edges.

There are several factors to enhance the field strength: (1) the potential of the metal which will enhance the field strength at the strip edge if the potential is positive (MOS effect), (2) the positive oxide charge in the interface between the SiO_2 and the bulk Silicon which will enhance the field strength in the strip edge (Oxide charge), (3) ionizing radiation which will further increase the oxide charge, to a surface density of about 5×10^{12} e/cm^2 [5] (Radiation), and, furthermore, (4) defects which will generate a concentration of electric field (Defect). The avalanche breakdown electric field of the Silicon is 20 to 30 V/μm [6], and if the field strength combined all the effects is above the threshold, the carriers will be accelerated and start to cause avalanche multiplication (impact ionization) or the "micro-discharge".

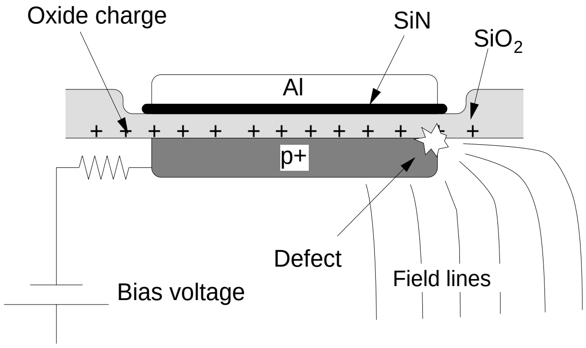

Fig. 1 P-strip of the ordinary Silicon microstrip detector

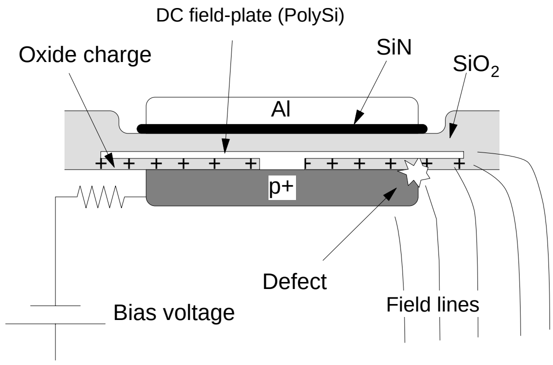

Fig. 2 "DC field plate" in the p-strip structure

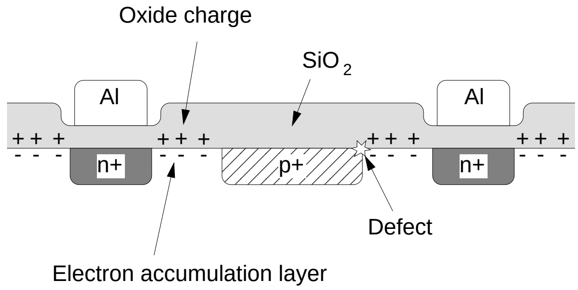

Fig. 3 Ordinary n-side structure: n-strips and p-stop structure between the n-strips

In order to reduce the electric field in the Silicon, an idea of "DC field-plate" was introduced. The structure is shown Fig. 2. A field plate in the SiO_2 is added, extending wider than the p-implant and contacting the p-implant directly. The breakdown of SiO_2, 1000 V/μm, is much higher than that of the Silicon, and by having the DC contacting field plate which edge is sandwiching the SiO_2, the highest electric field is in the SiO_2, thus much more immune to the microdischarge. The DC field-plate was made of Polysilicon simultaneously in the process of the Polysilicon bias resistor fabrication, and thus the same number of steps of the fabrication were kept.

The onset of the microdischarge was measured in the leakage current and in the noise measurement where a steep increase of leakage current or noise amplitude was observed for the ordinary structures. With an extension of 3 μm over the p-strip width, very little increase of the leakage current was observed and the onset of microdischarge noise was improved about factor 2 after the ionization dose of 15 kGy gamma irradiation.

III. MICRO-DISCHARGE IN THE N-SIDE

A new study was made on the microdischarge in the n-side. A typical cross section of the n-side is shown in Fig. 3. In between the n-strips, an extra structure is placed. The structure is called "p-stop" and cuts the "accumulation layer".

When the n-strip is biased to deplete the Silicon bulk, there are two possible areas where the electric field gets strong: one is the edge of the n-strips and the other is the edge of the p-stop. If the accumulation layer is highly resistive, the n-strip edge will be the strongest, while if it is less resistive than the bulk, the edge of the p-stop will be the strongest. The situation is worse after the type inversion of the bulk occurs. Before the type inversion, the electric field gets off when the depletion reaches the n-side, while after the inversion, the electric field gets off once the bias voltage is put on, in addition to the enhanced oxide charge due to the radiation damage.

A prototype detector, a double-sided Silicon microstrip detector, was made which had a similar "DC field-plate" as in the ref. [4] on the n-strips and on the p-strips in order to identify the microdischarge in the edge of the n-strips. The tests before and after an proton irradiation showed very similar increase of the leakage current and the microdischarge noises, thus suggested that the location of the weakest point was not at the edge of the n-strips.

A new prototype detector of the n-strip readout on n-bulk was also fabricated with the ATLAS Silicon microstrip detector specification (ATLAS97). The pitch of the strips was 80 μm with the n-strip implant width of 18 μm and the readout metal width of 16 μm. The p-stop structure was an "individual p-stop" where an atoll-type p-stop structure was surrounding each n-strips [7] [8]. The specification was the same as listed in Table 1 except the p-stop structure.

Being biased at 500 V, the ATLAS97 detectors, non-irradiated, were inspected with the infra-red camera. The image showed multiple of local spots emitting infra-red light which was indicating that the avalanche breakdown was occurring. An image is shown in Fig. 4 which visualized that the hot spot was associated with a sort of defect and at the boundary of the p-stop structure. Other spots were also aligned at the p-stop boundaries. The strongest field was at the edge of the p-stop structure.

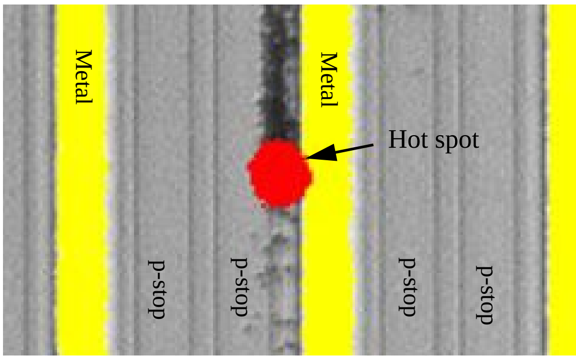

Fig. 4 Hot spot image overlapped with the visible image of the strips. The spot was taken at a bias voltage of 500V. Readout metals and the p-stop structures are noted in the figure.

IV. Novel p-stop structure

Once the location of the microdischarge was identified to be the edge of the p-stop, it was natural to apply the idea of the "DC field-plate" to the structure. An ATLAS spec prototype detector was fabricated incorporating the novel p-stop structure. A cross-section of the structure is shown in Fig. 5. The base p-stop structure was a continuous p-frame surrounding the n-strips, called "full-frame p-stop". The Polysilicon was added over the p-stop extending by 4 µm over the width of the p-stop and contacting the p-stop via a cut in the SiO_2 passivation layer. The dimensions of the strips are noted in the figure and the parameters are summarized in Table 1

V. Irradiation results

A. Proton irradiation at KEK

The prototyped novel p-stop detectors were irradiated to two fluences, one at KEK and the other at CERN. At KEK, a primary beam from the 12 GeV proton synchrotron (PS) was extracted to the EP1A beamline where the irradiation samples were set [9]. The fluence received at KEK was ~3×10^{13} p/cm^2, in which protons consisted of ~2×10^{13} p/cm^2 and a halo of neutrons of ~1×10^{13} p/cm^2 over the detector area. The irradiation took 3 hrs. and the samples were cooled at 4 °C during the irradiation and 16 days after the irradiation in the beamline. After extraction from the beamline, they were stored at 0 °C. As for a reference, a conventional p-stop detector, the nn80AC detector [8], was irradiated simultaneously.

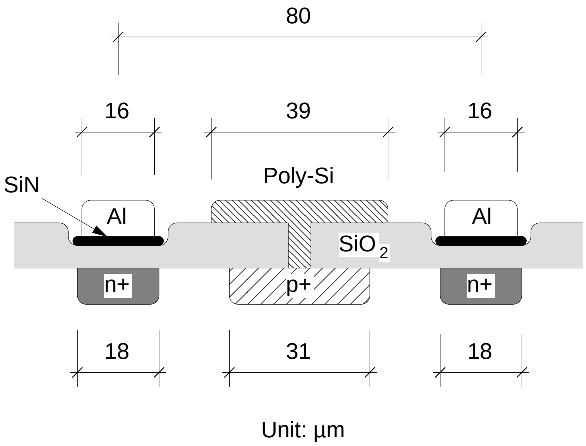

Fig. 5 Novel p-stop structure with DC-field plate over the p-stop implantation.

Table 1.
Parameters of the ATLAS spec n-on-n detector with the novel p-stop structure

Detector type:	N-bulk, n-strip, AC-coupled, Single-sided
Bulk:	N-bulk, 300 µm thick
Resistivity:	4~8 kΩcm
Size (Outer):	6.36 cm × 6.4cm (width × length)
N-sensitive area:	Width: 770 × 80µm =61.6 mm
	Length: 62 mm
P-side structure:	DC-coupled pad
Surface protection	SiO_2 passivation
Number of N-strips:	(128 × 6 zones=768 readouts)+2 dummies
N-strip isolation:	Novel p-stop structure (full-frame common)
N-strip parameters:	
Polysilicon bias resistor:	1.5±0.5 MΩ
Strip pitch:	80 µm
Readout pitch:	80 µm
Implant width:	18 µm
Width of Al. readout:	16 µm
P-stop width(implant/Poly):	31/39 µm
AC-coupling:	SiO_2 0.25µm+SiN 0.05µm

Leakage current of the two detectors were measured before and after the irradiation and is shown in Fig. 6. The measurement before the irradiation was done at the room temperature, and after the irradiation at 0 °C. HPK-p-03 is the conventional p-stop detector, and HPK-p-23 the novel p-stop detector.

Immediately seen in the figure is that the leakage currents of the irradiated detectors increased 3 orders of magnitude, which is typical for the irradiated detector. In comparison of the conventional and the novel p-stop structures, there are clear distinction: the conventional p-stop showed a rise of the leakage current above 150 V bias voltage, while the novel p-stop structure no increase of the current up to the measured bias voltage of 260 to 300 V.

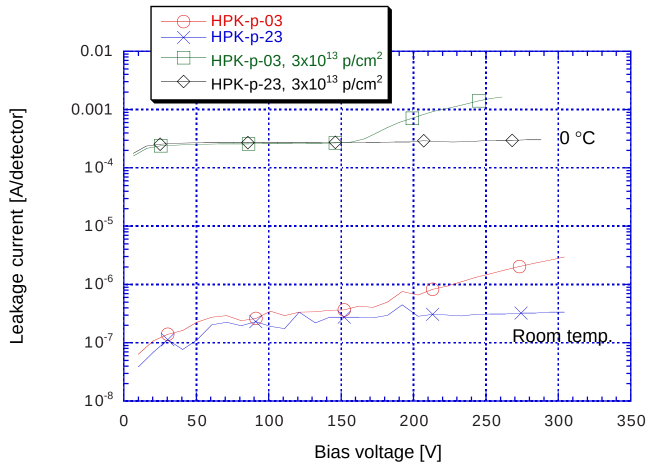

Fig. 6 Leakage currents of the conventional and the novel p-stop structures before and after the proton irradiation of 3 x 10^{13} p/cm^2.

B. Proton irradiation at CERN

The novel p-stop detector was also irradiated at CERN to the 24 GeV/c protons from its PS to a fluence of 3 x 10^{14} p/cm^2, the maximum fluence expected for the Silicon microstrip detector in the ATLAS experiment at LHC over 10 years. The reference detector was the ATLAS spec "individual p-stop" n-on-n detector in this irradiation. The detectors were irradiated for 8 days at a temperature of -8 °C. The detectors were biased at 150 V and the leakage currents were monitored during the irradiation.

The leakage currents as a function of time are shown in Fig. 7. In the figure, HAM97-8 is the conventional p-stop detector (individual p-stop) and HAMNP-21 the novel p-stop detector. There were several jumps, at 90, 115, 130, and 180 hrs. These were intermissions for the access of the cooling box in order to replace other samples. The detectors were warmed up to the room temperature when the box was accessed.

The conventional p-stop detectors, with the accumulation of fluence, induced leakage current at much higher rate than the novel p-stop detectors. The currents of the conventional p-stop detectors, however, annealed very quickly once the beam was off and warmed up. The novel p-stop detector did not show such behaviour and the leakage current increased steadily with the accumulation of the fluence.

When the novel p-stop detector was warmed up, the current increased. This can be understood as: With the warm-up, the bulk damage annealed quickly (beneficial annealing) and then the depletion depth got deeper, thus increasing the bulk leakage current which was an volume effect.

VI. Conclusion

Further studies on the microdischarge was carried out in the

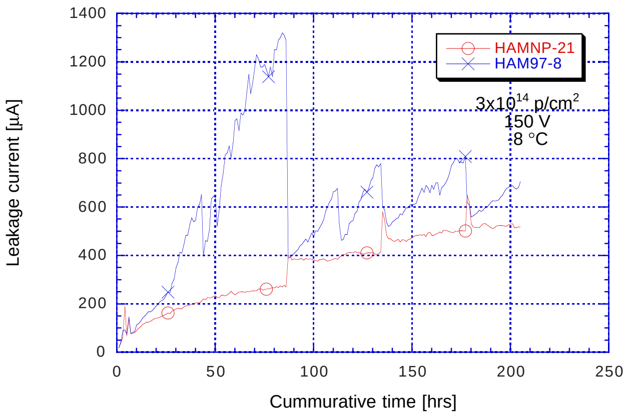

Fig. 7 Leakage currents during the irradiation at a bias voltage of 150 V and cooled at -8 °C. The total fluence was 3 x 10^{14} p/cm^2.

n-side. The discharge location was investigate visually with the highly sensitive infra-read camera and identified at the edge of the p-stop structure. The p-stop structure was a requisite in the n-side in order to isolate the n-strips in the n-side. The p-stop cuts the accumulation layer in the surface of Silicon due to the positively charged oxide charges in the interface between the SiO_2 passivation and the bulk Silicon.

In order to suppress the high electric field at the edge of the p-stop in the n-side, a novel p-stop structure, a p-stop structure with the "DC field plate", was invented. A prototype detector was fabricated and tested before and after the proton irradiations, one fluence at 3 x 10^{13}, and the other at 3 x 10^{14} p/cm^2, the latter being the maximum fluence expected for the ATLAS Silicon strip detectors over 10 years of operation.

Only the leakage current behaviour was measured so far for the irradiated detectors, however, the leakage current performance of the novel p-stop detector was excellent. The detectors suppressed the increase of the leakage current above a bias voltage and the increase of leakage current along the accumulation of fluence. The results suggested that the novel p-stop structure had suppressed the microdischarge in the edge of the p-stop structure.

VII. Acknowledgements

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