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Novel p-stop structure in n-side of silicon microstrip detector

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

[a]*Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba City, Ibaraki-ken 305-0801, Japan*
[b]*Physics department, Hiroshima University, Higashi-Hiroshima 739-8526, Japan*
[c]*Education department, Kyoto University of Education, Kyoto 612-0863, Japan*
[d]*Physics department, Okayama University, Okayama 700-8530, Japan*
[e]*Semiconductor division, Hamamatsu Photonics Co. Ltd., Hamamatsu 435-8558, Japan*

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Abstract

In order to suppress the high electric field at the edge of the p-stop structure, a novel p-stop structure with DC field-plate was proposed. An n-in-n detector with the novel p-stop structure showed no onset of microdischarge, before and after proton irradiation of fluences of 3×10^{13} and $3\times10^{14}\,\mathrm{p/cm^2}$.

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Keywords: P-stop; N-side; N-in-n; Silicon; Microstrip; Detector

1. Introduction

Silicon microstrip detector has become a common device in particle physics experiments to measure the position of charged particles in high precision. An example of large-scale application of the device is the Semiconductor Tracker (SCT) of the ATLAS detector at the large hadron collider (LHC) [1]. A requirement in such experiment is to tolerate high radiation environment. When a silicon detector is placed in the radiation environment of charged particles and neutrons, defects are generated in the bulk of silicon and electrically active defects change the net doping concentration of donor/acceptors. The silicon bulk inverts from n-type to p-type and the full depletion voltage increases as the radiation accumulates. In the SCT, the fluence of particles is expected to be equal to 2×10^{14} neutrons/cm^2 (1-MeV-neutron equivalent) and the maximum operation voltage to be about 500 V, in the part nearest to the interaction point.

*Corresponding author. Tel.: +81 29 864 5791; fax: +81 29 864 2580.
E-mail address: unno@post.kek.jp (Y. Unno).

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The silicon detector collects the electron–hole pairs generated in the depleted region by the incident charged particles. The depleted region starts from the p–n junction and reading out the signals from the p–n junction side enables the operation of the detector in a partially depleted mode. For the common bulk type of silicon detectors, i.e., n-type for high resistivity and, thus, low depletion voltage, a possible type of detector is to make the readout strips in n-type, the n-in-n detector. After heavy irradiation, the n-strips form p–n junctions due to the type inversion of the bulk.

In order to make the n-in-n detector work, the n-strips must be isolated resistively from the adjacent n-strips. The surface of the silicon bulk is covered with silicon dioxide (SiO_2, the "passivation" layer) for insulation and protection. The silicon dioxide–silicon interface contains surface states and, additionally, the insulator film that are charged up positively. The positive charge attracts the majority carriers from the n-type bulk, electrons, and forms an electrically conductive path between the n-strips. The electron layer in the silicon surface is called "accumulation layer". The conductivity in the silicon surface was demonstrated experimentally, e.g., in Ref. [2].

To interrupt the accumulation layer, a common practice is to implant p-type zones ("p-stop") surrounding the n-strips, thus having p–n junctions between the n-strips. As the bias voltage is applied, the p-stops will have a potential from that of the n-strips due to the influence of the potential applied on the other side. Because of the conductivity of the accumulation layer, the n-strips reach the edge of the p-stops. This may cause a high electric field at the edge of p-stops, especially where geometrically sharp defects exist. If the electric field is stronger than about 30 V/μm, it induces the avalanche breakdown [3]. We call small pre-breakdown "microdischarge" that was characterized by the increase of leakage current and noise [4].

In this paper, we describe the concept of our previous invention of "DC field-plate" suppressing the microdischarge in the p-side of the silicon microstrip detector. Then, we describe the observation of the microdischarge in the n-side and introduction of the novel p-stop structure in order to suppress the microdischarge. Lastly, we present the performance of the n-in-n detector with the novel p-stop structure in the irradiation tests.

2. DC field-plate

The microdischarge in the p-side of the n-bulk AC-coupled silicon microstrip detector was studied systematically [4]. The microdischarge along the edge of strips was visualized by an infrared-sensitive camera [5]. Further studies have shown that the microdischarge starts at localized spots, e.g., at the defects at the edge of the strips where the electric field is strong enough. A schematic structure of the conventional p-side is shown in Fig. 1. The readout metal is placed over the p-strip by sandwiching an insulator layer (SiO_2) or layers (SiO_2 + silicon nitride (SiN)). The p-strip is biased through a resistor. The maximum field in the silicon is at the edge of p-strip where the field lines concentrate. The interface oxide charges enhance the field strength at the edge further.

The field strength at the edge of the p-strip can be modified by the width of the readout metal, depending on the relative potential of the metal to the p-strip. In order to reduce the field strength at the edge of the p-strip, independent from the width and the potential of the metal, an idea of "DC field-plate" was introduced [4]. A schematic structure of the p-strip with DC field-plate is shown in Fig. 2. A layer of polysilicon was embedded inside the SiO_2, extended wider than the p-strip and connected to the p-strip directly. As connecting the p-strip and the polysilicon layer in DC, the maximum field is moved to the edge of DC field-plate inside the SiO_2, where the breakdown voltage is as high as 1000 V/μm.

3. Microdischarge in n-side

A schematic structure of the conventional n-side is shown in Fig. 3. The p-stop structure is in between the n-strips and cuts the accumulation layer. If the accumulation layer is conductive and the potential of the n-strips reach the p-stop, the

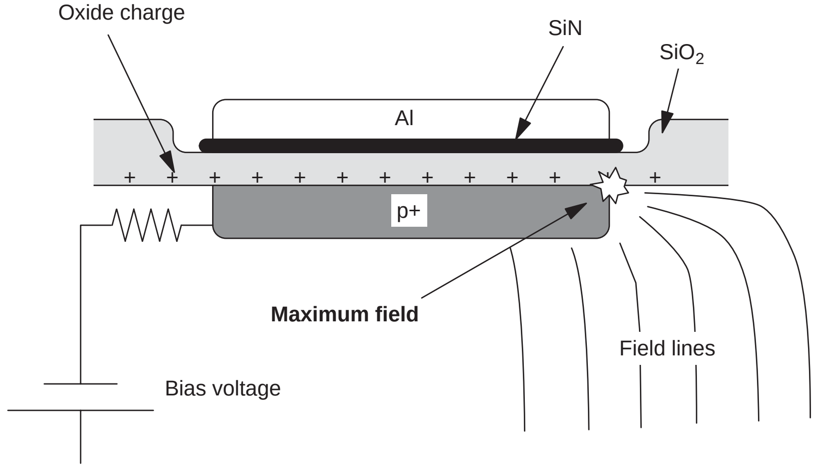

Fig. 1. Conventional p-side structure of AC-coupled silicon microstrip detector.

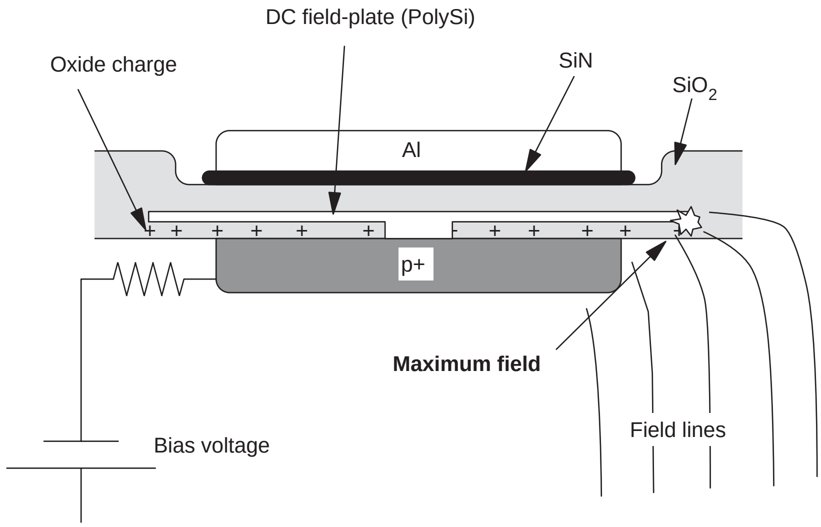

Fig. 2. P-strip structure with DC field-plate of AC-coupled silicon microstrip detector.

maximum field is at the edge of the p-stop, and if there is a sharp defect, the maximum field at the defect may exceed the breakdown voltage of the silicon, thus, inducing the microdischarge.

Two types of detectors with conventional p-stop structures were fabricated. One was a double-sided silicon microstrip detector that had the DC field-plate structure both in the p-strips and in the n-strips. The detector, before and after proton irradiation, showed very similar onset of the leakage current and noise, thus suggested the location of microdischarge be not at the edge of the p- or n-strips.

The other was an n-in-n detector along the ATLAS silicon microstrip detector specification, the nn80AC detector [6]. The pitch of the strips was 80 μm with the width of n-strip implant of 18 μm and the width of readout metal of 16 μm. The p-stop was an ‘‘individual’’ p-stop structure where an atoll-type p-stop structure was

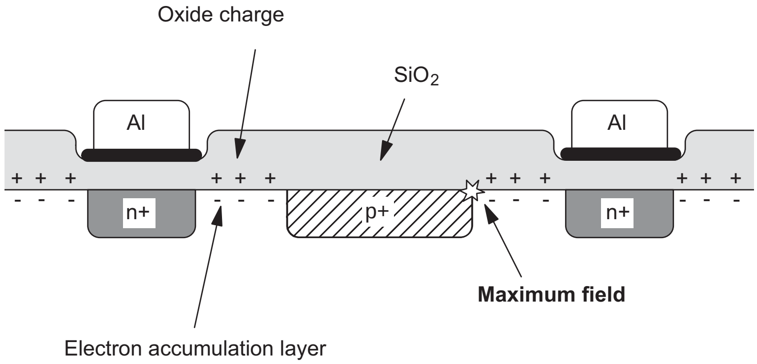

Fig. 3. Conventional n-side structure of AC-coupled silicon microstrip detector: n-strips and p-stop structure between the n-strips.

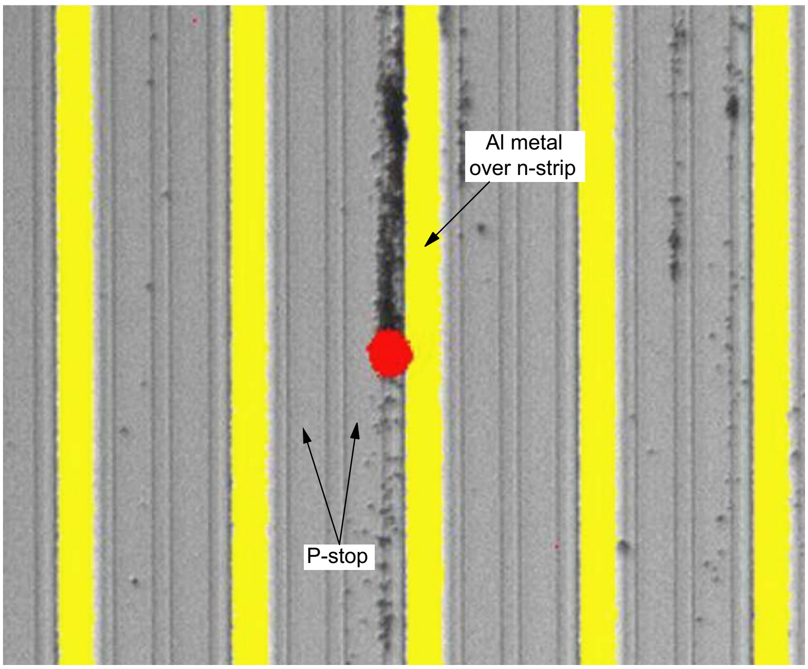

Fig. 4. Image of hot spot overlapped with the visible image of strips. The spot was taken at bias voltage of 500 V. Readout metal and p-stop area are noted in the figure.

surrounding each n-strip [7]. By biasing at 500 V, number of the detectors, non-irradiated, showed onset of microdischarge. The inspection with the infrared-sensitive camera showed number of localized hot spots. An image is shown in Fig. 4. The hot spot is associated with a kind of defect, at the edge of the p-stop structure. Other spots were also aligned at the edge of the p-stops. The two detectors were confirming that the maximum field was at the edge of the p-stop.

4. Novel p-stop structure

In order to suppress the microdischarge at the edge of p-stop, we applied the concept of the DC

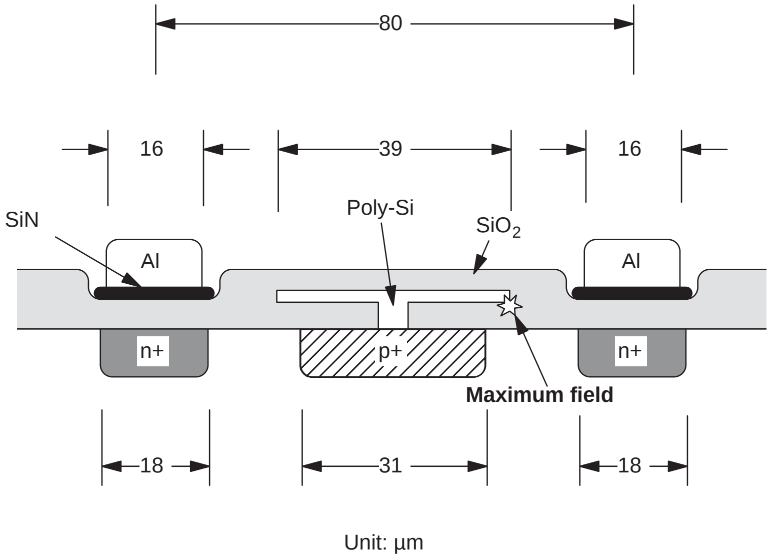

Fig. 5. Novel p-stop structure with DC-field plate over p-stop implantation.

field-plate to the p-stop structure. A schematic of the novel p-stop structure is shown in Fig. 5. The polysilicon DC field-plate was embedded inside the SiO_2, extended wider than the p-stop and connected to the p-stop directly. An n-in-n detector was fabricated incorporating the novel p-stop structure to a p-stop structure of continuous p-frame surrounding the n-strips ("full-frame common"). Dimensions of the structure are specified in the figure and the parameters are summarized in Table 1.

Table 1
Parameters of n-in-n detector with novel p-stop structure

Detector type	Single-sided AC-coupled n-strip readout in n-bulk silicon wafer
Size (Outer)	63.6 mm × 64.0 mm (width × length)
Bulk	N-bulk, ⟨1 1 1⟩ orientation, 300 μm thick
Resistivity	4–8 kohm-cm
N-side	
Strip area	770 strips × 80 μm = 61.6 mm
Strip length	62 mm
N-strip parameters	
Strip pitch	80 μm
Readout pitch	80 μm
Implant width	18 μm
Width of Al readout metal	16 μm
AC-coupling insulator	SiO_2 0.25 μm + SiN 0.05 μm
Bias resistor	Polysilicon 1.5 +/−0.5 Mohm
N-strip isolation	Novel p-stop structure (full-frame common)
P-stop width (p^+ implant/polysilicon)	31/39 μm
Surface protection	SiO_2 passivation
P-side	
Implant	61.6 mm × 62 mm pad
Contact	DC coupled Al metal

5. Irradiation results

5.1. Proton irradiation at KEK

The n-in-n detectors with the novel p-stop structure were irradiated at High Energy Accelerator Research Organization (KEK) and at European Organization for Nuclear Research (CERN), together with the n-in-n detectors with the conventional p-stop structure for comparison. At KEK, the samples were set in the EP1A beamline and irradiated by the primary beam extracted from the 12 GeV proton synchrotron (PS). The irradiation setup was described elsewhere [8]. The fluence received was ~3×10^{13} p/cm^2, where protons were ~2×10^{13} p/cm^2 and halo of neutrons ~1×10^{13} p/cm^2 over the detector area. The samples were cooled at 4 °C and irradiated in 3 h. They were left in the tunnel of the beamline for 16 days after irradiation. After extracting from the beamline, they were stored at 0 °C.

The leakage currents of two detectors, before and after irradiation, are shown in Fig. 6. HPK-23 was the novel p-stop and HPK-03, the conventional p-stop detector. The samples were measured at room temperature before irradiation and at 0 °C after irradiation.

The irradiation increased leakage currents by three orders of magnitude, which is expected typical for the accumulated fluence. The novel p-stop detector showed an improvement: the novel p-stop detector showed no onset of leakage current up to the measured bias voltage of 260 or 300 V, while the conventional p-stop detector onset around 150 V.

5.2. Proton irradiation at CERN

The novel p-stop and the conventional p-stop detectors were also irradiated at CERN to the 24 GeV/c protons from its PS to a fluence of 3×10^{14} p/cm^2, the proton equivalent of 2×10^{14} neutrons/cm^2 including the damage factor by protons for neutrons. The detectors were biased at 150 V and irradiated for 8 days at temperature of −8 °C.

The leakage currents were monitored along the irradiation and are shown in Fig. 7. HAMNP-21 was the novel p-stop and HAM97-8 the conventional p-stop detector. The jumps at 90, 115, 130 and 180 h were caused by the intermissions of irradiation and warm-up of the detectors for the access to the cooling box in order to replace other samples.

The leakage current of the conventional p-stop detector increased at high rate with accumulation of the fluence, and annealed very quickly once the beam was off and the detector was warmed up. The novel p-stop detector did not show such behavior and the leakage current increased steadily. The high rate increase and quick annealing of

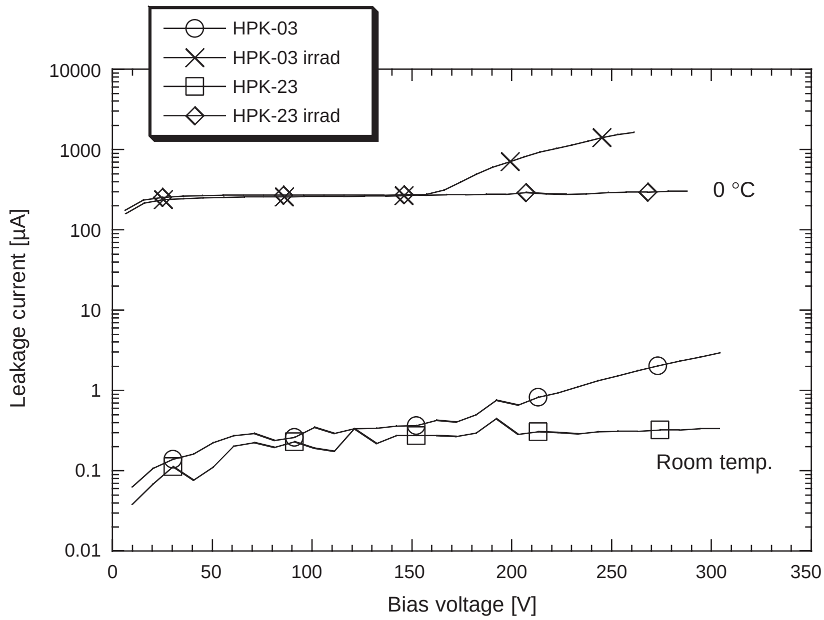

Fig. 6. Leakage currents of conventional (HPK-03) and novel p-stop (HPK-23) detectors before and after irradiation of fluence of 3×10^{13} p/cm^2.

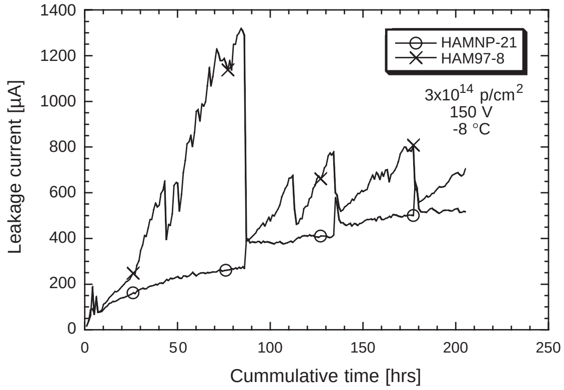

Fig. 7. Leakage currents of conventional p-stop (HAM97-8) and novel p-stop (HAMNP-21) detectors along irradiation at bias voltage of 150 V and temperature of $-8\,^{\circ}$C. The fluence was null at start and 3×10^{14} p/cm^2 at end.

the current could be the indication of micro-discharge, enhanced by the oxide interface charges with irradiation.

When the novel p-stop detector was biased after the warm up, the leakage current started slightly higher values and decayed quickly to the current at steady increase. This could be an artifact that the temperature of the detector was not settled to the irradiation temperature at the resumption of irradiation.

6. Summary

A possible type of silicon microstrip detector that works efficiently in high radiation environment is to use n-type strips. The n-strip forms the p–n junction when the silicon bulk inverts to p-type after heavy irradiation. The detector with n-strips in n-type bulk wafer, n-in-n detector, requires a p-stop structure between the n-strips in order to interrupt the accumulation layer due to the silicon oxide and silicon oxide–silicon interface charges. In the n-in-n detector, the edge of p-stop structure is expected to generate a high electric field and possible onset of microdischarge. An infrared-sensitive camera confirmed the hot spots at the edge of p-stop structure.

In order to suppress the high electric field at the edge of p-stop, a novel p-stop structure, a p-stop structure with DC field-plate, was proposed and an n-in-n detector was fabricated. In comparison with an n-in-n detector with a conventional p-stop structure, the novel p-stop detector showed no onset of microdischarge, before and after proton irradiation of fluences of 3×10^{13} and 3×10^{14} p/cm^2.

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