Characterization of n-on-p detectors with different p-stop and p-spray structures by simulations and measurements

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Abstract

In this paper the simulation and measurement results of the n-on-p MCz-Si detector structures are described. The five different p-stop and p-spray ion implantation combinations are studied. The diodes are electrically characterized by C-V and I-V measurements and the computer simulations of the n-on-p strip detector are done using Silvaco Virtual Wafer Fab (VWF) software. The cross-section of the n-on-p strip detector is simulated in two-dimensions with different dose of p-stop and p-spray. Simulation results and measurement results are compared.

1. Introduction

Silicon detectors are widely used in high energy physics experiments and are in construction or planned for the future experiments such as those at the Large Hadron Collider (LHC) and its proposed upgrade to the Super-LHC. For the Super-LHC experiments the luminosity is upgraded to 10^{35} $cm^{-2}s^{-1}$, which has 10 times higher luminosity than the LHC, so the innermost tracking detectors have to face fluencies above 10^{16} cm^{-2} of fast hadrons after five years operation accumulating an integrated luminosity of 2500 fb^{-1} [1,2]. Under these conditions, detector performance may be limited by a large number of defects introduced into the device.

The most commonly used detector type is p-on-n, where the detector has an n-type bulk and a p-type (structured) front electrode. The bulk radiation damage results in a change of the doping concentration. A progressive irradiation of the initial n-type silicon leads to the inversion of its type of conductivity, turning in p-type silicon. The type inversion of p-on-n detector is posing a problem since the high electric field is switching from the structured readout side to the backside of the detector [3].

Instead, the p-type silicon does not suffer of type inversion after strong irradiation. The n-on-p detectors do not type invert because they already are p-type and the structured read-out side will be the one with the high electric field before and after irradiation. When the read-out side is at the high electric field contact the charge collection efficiency is improved because the n-side do not suffer from the space charge sign inversion (SCSI) and consequently it presents a higher charge collection efficiency (CCE) than p-on-n detectors beyond the SCSI point [4,5]. Moreover, n-on-p detectors collect electrons, which have three times higher mobility than that of holes, collected in p-on-n detectors. Consequently, the trapping of charge carriers within their lifetime is reduced [6]. Therefore it is preferable to process n-type strips on the p-type substrate especially in the cases of close-to-beam applications, where highly non-uniform irradiation is present.

The n-on-p detectors are expected to be more radiation hard than standard p-on-n detectors. These detectors are more complex as they need an extra surface insulation. This insulation is achieved by a blank surface implant, named p-spray, or by p-type junctions, named p-stops. P-spray is a lightly doped layer over the wafer surface and p-stops are heavily doped guard rings between the n-type guard rings.

2. Electrical characteristics

The detectors used in this study were processed at the Microelectronics Center of Helsinki University of Technology. The starting material was p-type 300 µm thick Si wafer. The n+ -implanted area of the diode is surrounded by two 100 µm wide guard rings, one p-type and and another n-type. Wide guard rings are then surrounded by a multi-guard ring structure of sixteen 16 µm rings where p-type and n-type guard rings alternate. The pitch of the device is 16 µm. The top view of the device structure is shown in Fig. 1 [6].

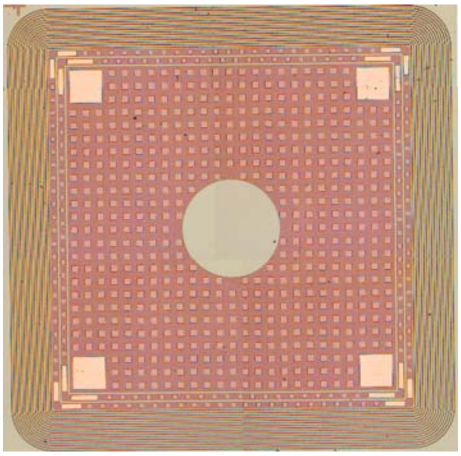

Fig. 1. N-on-p detector.

A probe station, Signatone S-1160, was used for electrical probing. The diodes were connected to the measuring electronics by two probe needles; one was connected to the n-type pad and the other one to the wide n-type guard ring. The negative bias voltage was connected to the bottom of the detector (p+ backside). N-type pad and the wide n-guard ring were connected to the ground. The wide p-guard ring was left floating, as well all sixteen narrow guard rings. Two Keithley 2410 SourceMeters were used to apply voltage and measure leakage currents. One of the SourceMeters was used to apply the negative bias voltage to the backside of the detector. The detectors were measured above the full depletion voltage, up to 240 V.

The capacitance was measured with a HP 4284A LCR-meter operated at 1 MHz. All measurements were carried out at a temperature between 22 °C and 23.5 °C. The measurements of electrical characteristics, current-voltage and capacitance-voltage, are presented for detectors with different p-spray and p-stop combinations. The combinations are:

P 042: p-stop $1x10^{15}$ cm^{-2} only
P 068: p-stop $1x10^{15}$ cm^{-2} and p-spray $1x10^{12}$ cm^{-2}
P 069: p-stop $1x10^{15}$ cm^{-2} and p-spray $3x10^{12}$ cm^{-2}
P 082: p-stop $1x10^{15}$ cm^{-2} and p-spray $5x10^{12}$ cm^{-2}
P 083: p-spray $3x10^{12}$ cm^{-2}.

A. Leakage current

The total leakage current and the pad leakage current were measured. The total leakage current varied between couple nanoamperes to couple microamperes depending on the sample at full depletion voltage (100 V from CV-curve below). From Fig. 2. can be seen that leakage currents start rapidly to increase after full depletion voltage and for samples P 069 and P 082 it happens already before reaching the full depletion. Leakage current continues to increase, but in this study it was limited to the maximum of 100 µA by Keithley 2410 SourceMeter. The pad leakage currents act as a typical detector leakage currents at low voltages (Fig. 3.). At higher voltages the P042 and P082 samples are more stable than other samples.

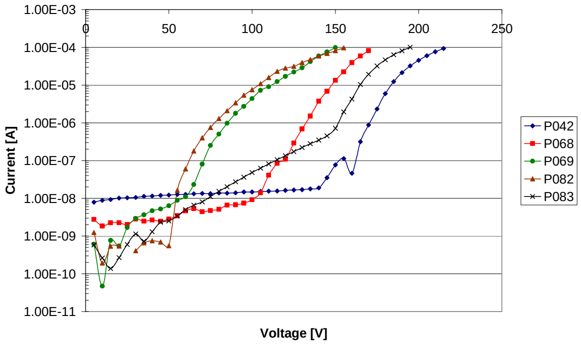

Fig. 2. The total leakage current measured from detectors as a function of applied reverse bias voltage. The scale of current is logarithmic.

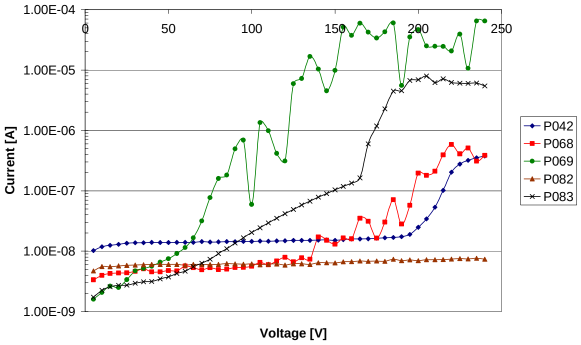

Fig. 3. The pad leakage current measured from detectors as a function of applied reverse bias voltage. The scale of current is logarithmic.

B. Capacitance-voltage

The CV-measurement results do not differ much between different samples (Fig. 4.). In Fig. 5. the inverse of squared capacitance $1/C^2$ is plotted as a function of applied bias to deduce the full depletion voltage. The voltage for full depletion is clearly seen at the kink of the graph. The full depletion voltage, extracted from CV measurements, is about 100 V for all samples.

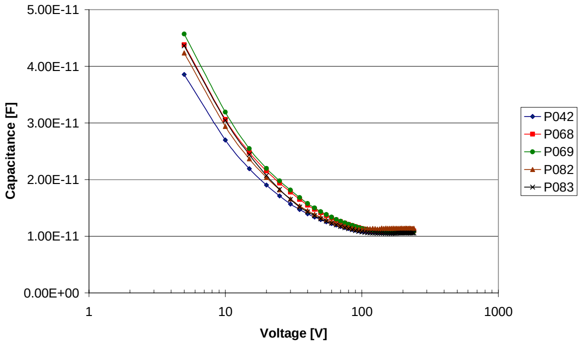

Fig. 4. Measured CV-curves as a function of applied reverse bias voltage. The scale of voltage is logarithmic.

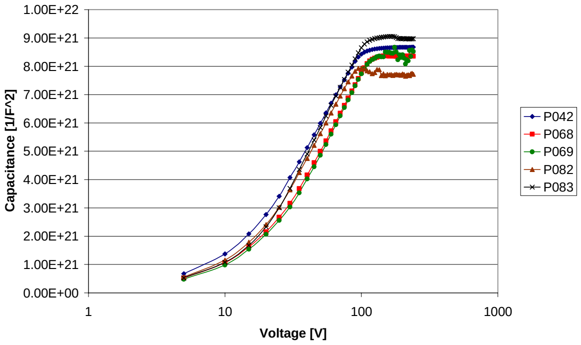

Fig. 5. Plot of $1/C^2$ as a function of reverse bias voltage. The scale of voltage is logarithmic.

3. Simulation of p-type detectors

Fig. 6. shows a schematic cross-section of a n-in-p detector with p-spray and p-stop implants, which was used for a two dimensional simulation. Simulations were made using Silvaco Virtual Wafer Fab software.

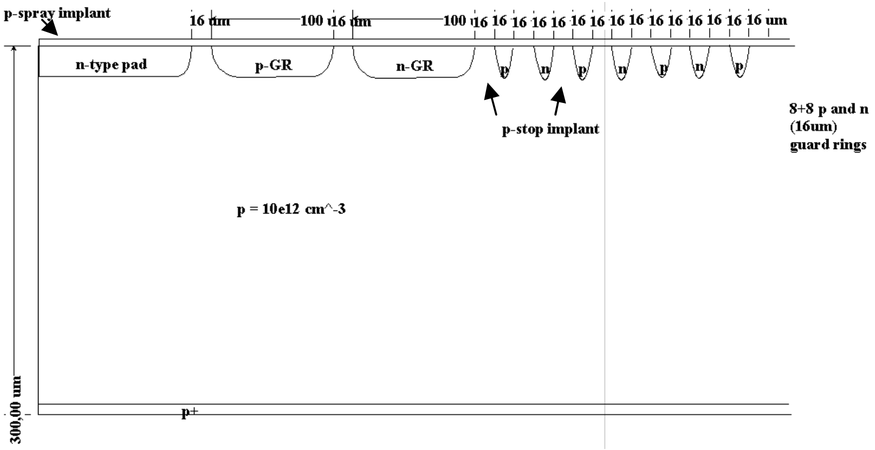

Fig. 6. The schematic cross-section of an n-on-p detector with p-spray and p-stop implants. Simulations were done using this model. All dimensions are in µm.

The simulated leakage current of n-on-p structure is shown in Fig. 7. The simulations do not show differences between leakage current for four combinations. Only the leakage current of P 083 detector differs from others where there is only p-spray implant present. In this case the leakage current is higher.

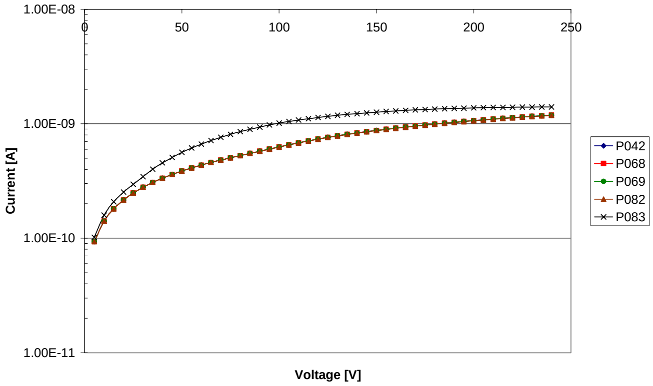

Fig. 7. The simulated leakage current of detectors as a function of bias voltage. The scale of current is logarithmic.

4. Discussion

The radiation hardness of silicon detectors can be increased by processing n-type strips on the p-type substrate. P-type detectors charge collection efficiency is improved because they do not suffer from the space charge sign inversion and they present higher charge collection efficiency than p-on-n detectors beyond the SCSI point. The electrical characteristics of p-type detectors can be engineered with different surface implantations. The implantations, p-spray and p-stops, affect to the full depletion voltage and the leakage current of the detector. The measurements of the detectors show that the leakage currents of the detectors act as a typical detector leakage currents at low voltages but after reaching the full depletion voltage, leakage currents increases rapidly. There is some variance in measured leakage current between the samples. Instead, simulated leakage currents are similar for all samples but P 083, where there are no p-stops at all. In this case the leakage current is higher than others. The measured CV-results do not differ much between the samples. The full depletion voltage, extracted from CV measurements, is about 100 V for all samples, which is lower than the full depletion voltages typically seen in n-type detectors. The low full depletion voltage is the advance of p-type detectors used in high energy physics experiments.

References

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