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RADIATION EFFECTS OF DOUBLE-SIDED SILICON STRIP SENSORS

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Abstract

A series of proton-beam irradiations was performed in order to investigate the radiation damage of silicon photodiodes and double-sided silicon strip sensors. Measurements were made for the leakage current, bias resistance, interstrip isolation, annealing, and responses to an infrared light pulse and β -rays. Some problems in the production of radiation-hard double-sided strip sensors were

observed. However, it has been shown that most of them can be resolved by adequately designing the strip structure, the implantation density and the materials used for various parts of the sensor. It is therefore possible to obtain a double-sided silicon strip sensor which works even after charged-particle irradiation of 20 kGy.

1 Introduction

A large system of double-sided silicon strip sensors (*DSSS*) will be used as an inner tracker of the SDC detector[1] at the Superconducting Super Collider (SSC). Silicon microstrip detectors have excellent position resolution, a high rate capability and excellent two-track separation, all of which are indispensable features for an SSC tracker. The *DSSS* has microstrip electrodes on both sides so that it can supply two-dimensional information while keeping the amount of material as small as possible. To make the best use of these advantages, it is to be installed in the vicinity of the beams, where the radiation level is so high that the dose will be more than 10 kGy ($= 1$ Mrad) after several years of running at the expected luminosity. Therefore, radiation hardness is a crucial requirement which must be met by the silicon tracker. Our goal is to develop sensors which can be used after irradiation of a few 10 kGy.

A series of irradiation tests of silicon sensors was performed using 65 MeV protons. Proton irradiation gives both the displacement damage in the bulk and the ionization damage on the surfaces. It therefore provides a more realistic experimental condition than either gamma or neutron irradiation. In this report we describe the results of both static and dynamic measurements of the irradiated sensors.

2 Experimental Procedures

2.1 Irradiated Sensors

Two kinds of silicon sensors were irradiated: photodiodes (Hamamatsu Photonics Co. Ltd. S1723-08) and microstrip sensors which were specially fabricated for this ir-

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radiation test. The general effects due to the radiation were investigated by using photodiodes, while the characteristic effects for microstrip structures were investigated by irradiating microstrip sensors.

The microstrip sensors had a sensitive area of $6.4 \times 6.4 \text{ mm}^2$ and a $300\text{-}\mu\text{m}$ thick n -type substrate. The strip pitch was $100 \text{ }\mu\text{m}$. These had strips on only one side with a plane implantation layer on the other side so that we could investigate the radiation effects specific to the strip structure separately on the p - n junction side (p -side) and on the n^+ ohmic side (n -side). The “ p -strip sensor” (PSS) had p^+ -implantation strips on the p -side, as shown in Fig. 1a, while the “ n -strip sensor” (NSS) had n^+ -implantation strips on the n -side, as also shown in Fig. 1b. The bias voltage was fed to each strip through a bias resistor from a bias ring which surrounds the sensitive area on the striped surface. The surfaces of the strip sensors were covered by a $0.2\text{-}\mu\text{m}$ thick SiO_2 layer. To avoid saturation of the preamplifier due to the leakage current, aluminum electrodes for the AC readout were printed on the outer surface of the SiO_2 layer. In some cases, the strip had an electrode which is directly connected to the implantation strip to measure the voltage of each strip. The outside of these structures were covered by another thin “passivation” layer to avoid any contamination by harmful ions etc. and for safer handling. Those strip sensors were fabricated by Hamamatsu Photonics Co. Ltd.

2.2 Beam and Setup

The sensors were irradiated by a 65 MeV proton beam from the AVF cyclotron at the Research Center for Nuclear Physics, RCNP, Osaka University. The proton beam was defocused so as to obtain good uniformity in space, and then collimated by a collimator in front of the sensor to make the beam spot match the sensitive area of the sensor. The beam profile was checked by observing scintillation light from a ZnS scintillator at the center of the scattering chamber with an image-intensifier tube before each irradiation, and was monitored with an MWPC during irradiation.

The sensors were mounted on a turntable in the scattering chamber at a suitable position (schematically shown in Fig. 2). The silicon sensor was moved in sequence to the correct position on the beam line for irradiation by turning the table. All of the sensors were irradiated at room temperature.

2.3 Dose Measurement

The beam intensity was monitored by a Faraday cup during irradiation, which was typically about 1 nA ($\approx 10^{10}$ protons/s) on the silicon sensor. The irradiation dose was, however, measured by detecting elastically scattered protons from a carbon target. A carbon target of $50 \text{ }\mu\text{m}$ in thickness was located at the center of the scattering chamber. The scattered protons were detected at an angle of 22.5° to the beam by an NaI counter. For a double check of the beam profile as well as the dose, a “Radcolor”, a paper-like monitor whose color changes with the irradiated dose[2], was attached to each sensor. The irradiation dose ranged from 10 to 60 kGy. The normalization error was estimated to be about $\pm 15\%$.

3 Experimental Results

3.1 Leakage Current

We examined the increase in the leakage current as a function of the irradiation dose. As shown in Fig. 3, the leakage current is roughly proportional to the dose. Equivalently, the increase in the leakage current per unit area is proportional to the fluence, $\phi(\text{protons}/\text{cm}^2)$,

$$\Delta I_{\text{leak}} = \alpha_p \times \phi,$$

assuming that all of the leakage current is generated in the bulk, where the leakage current constant (α_p) is measured in units of A/cm . In the present experiment, using a 65-MeV proton beam gives a value of $\alpha_p(65 \text{ MeV}) = 11 \times 10^{-17} \text{ A}/\text{cm}$. In a measurement using a 12-GeV proton beam [3], the value of $\alpha_p(12 \text{ GeV})$ was measured to

be 3×10^{-17} A/cm. The difference can be explained by the energy-loss difference of passing protons.

3.2 Bias Resistance

Two kinds of bias schemes were used for each side. The first scheme utilizes the “punch-through” effect through the depleted region on the *p*-side, while the “accumulation layer” of electrons formed at the interface of the substrate and the SiO₂ layer was put into use on the *n*-side.[4] The second scheme, which is mainly reported here, depended on a resistor string made of polycrystalline silicon, which will hereafter be called a polysilicon resistor. A polysilicon resistor having a length of about 400 μm was inserted between a bias ring and each strip. The non-uniformity of the resistance of the polysilicon resistors was measured to be less than 2.5% (rms) over the sensitive area. The absolute values of the resistance in the present samples were about 300 and 650 k Ω for *PSS* and *NSS*, respectively, in the present test.

The ratio of the voltage drop across the polysilicon bias resistor on *PSSs* to the dose for the irradiated strip sensors is shown in Fig. 4 as a function of the dose, where the bias voltage is 80 V. Since the leakage current is almost proportional to the dose (as shown in the previous section), this ratio should be almost proportional to the bias resistance. The figure shows that the change in the resistance is only 20%, even after irradiation of 40 kGy. The voltage drop, itself, was only about 50 mV for 40 kGy. This is much less than for the case of punch-through and the accumulation-layer, where the drops were more than 10 V for the same irradiation dose. In the case of the SDC silicon tracker, the bias resistor was planned to be 250 k Ω based on a compromise between the noise and the time response. Therefore, the voltage drop must be even smaller than in the present case where the bias resistance was higher. This result shows that the polysilicon resistor is sufficiently stable for use in high-radiation environments, like the SSC.

3.3 Interstrip Isolation

The isolation of the strips from adjacent strips is very important to minimize cross-talk. The isolation was investigated by measuring the interstrip current by biasing a strip relative to the adjacent strip. The voltage difference between the two neighboring strips was fixed at 1 V in this measurement. Fig. 5 shows the interstrip resistance as a function of the bias voltage. The figure shows that the interstrip resistance quickly approaches a plateau as the bias voltage is raised. It is also clearly seen that the isolation is quite stable against radiation. Since the two strips are connected via respective bias resistors, the resultant resistance is primarily determined by the resistance of the bias resistors, which are determined by other considerations.

On the *p*-side, the isolation depends on the *p-n* junction around the *p*⁺-strip. The interstrip resistance increases with the bias voltage and reaches the plateau. On the *n*-side, a blocking *p*⁺-implantation was inserted between the *n*⁺-strips for the isolation. The depleted region around the blocking *p*⁺-implantation is eventually connected to the depleted region which develops from the *p*-side at a certain bias voltage, which is about 50 V for a non-irradiated sensor.

As shown later, the substrate type changes from *n*- to *p*-type after the irradiation of protons. The type of the silicon between the *p*-strips, however, remains “*n*” due to electron accumulation near to the interface to the SiO₂ layer. Thus, isolation on the *p*-side is realized even after irradiation, as shown in the figure. On the other hand, the *n*⁺-strip on the *n*-side is surrounded by an inverted “*p*”-substrate and blocking *p*⁺-implantations after type inversion. The interstrip isolation on the *n*-side is therefore realized at a very low bias voltage for irradiated sensors, as shown in the figure.

The present result shows that interstrip isolation is sufficiently achieved both before and after type inversion.

3.4 Temperature Effects on the Annealing

Some of the irradiated sensors were kept at 0 °C ("Cold" sensors), while others were kept at room temperatures ("Warm" sensors). The "Warm" sensors show a faster decrease in the leakage current than the "Cold" sensors.

The depletion voltages of those two groups were determined by measuring their capacitance. The elapsed time dependence of the depletion voltage is shown in Fig. 6, where a definite increase in the depletion voltages was observed for the "Warm" sensors". This phenomenon is called "reverse annealing". In contrast, the depletion voltage did not increase for the "Cold" sensors, and even decreased in some cases. Therefore, the bias voltage for the depletion does not have to be raised after irradiation if they are kept at 0 °C. This result is consistent with reports by the Los Alamos group and others in this symposium.[5]

3.5 Type Inversion of the Substrate

The type-inversion phenomenon was observed by illuminating a *PSS* by an infrared LED. This measurement is schematically shown in Fig. 7. In order to observe the development of the depletion region, we used two different light sources with wavelengths of 850 nm and of 1150 nm with a dispersion of 100 nm. The mean free path of 1150 nm light in silicon was measured to be about 400 μm , which is longer than the thickness of the sensor. On the other hand, 850 nm light has a mean free path of about 30 μm . Thus, the light is completely absorbed at the illuminated surface in this case.

When the sensor is not fully depleted, the pulse height due to the LED has a positively increasing relation to the depletion depth through which the light passes. The depletion region starts from the *p*-side in the *n*-type substrate. On the contrary, it starts from the *n*-side after type inversion. As shown in the figure, the pulse height for 850 nm light strongly depends on the side from which the depletion starts. On the other hand, the pulse height depends primarily on the depletion depth in the case of 1150 nm light. The expected variation in the pulse height is shown in Fig. 7, where

the direction of the development of the depletion region is indicated by an arrow.

Fig. 8a shows the pulse height as a function of the bias voltage for non-irradiated sensors. Compared to 1150 nm light, 850 nm light injected on the *p*-side produces a larger signal at low bias voltages, as expected. On the other hand, the dependence of the pulse height on a sensor irradiated to 20 kGy is shown in Fig. 8b, where the variation is consistent with the behavior expected in a *p*-type substrate. Therefore, these observations are consistent with bulk-type inversion from *n* to *p*. [6] Inversion was observed at an irradiation dose of about 10 kGy.

3.6 Radiation Effects on the Pulse Height

A Sr- β source test was employed to measure the pulse height of a *PSS* which had been irradiated with a dose of 20 kGy. We fitted both the pedestal and the β -ray signal distribution with Gaussian and Landau distributions, respectively, to obtain the mean value. The net pulse height is the difference between the two mean values.

Fig. 9 shows the dependence on the bias voltage. The irradiated strips showed a degradation in the pulse height of about 5% at 150 V, compared with the non-irradiated one.

4 Summary

The present series of tests showed that: 1) polycrystalline silicon is an adequate material for a bias resistor in high-radiation environments; 2) quite good and stable interstrip isolation can be realized by interstrip p^+ -implantation, even after the type inversion; 3) the reverse annealing effect after the irradiation was shown to be suppressed if the detectors are kept at 0 °C; 4) the LED test clearly showed type inversion from *n*- to *p*-type; 5) a sensor irradiated by 20 kGy protons showed a degradation in the pulse height by about 5% at a bias voltage of 150 V.

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References

- [1] Solenoidal Detector Collaboration, "Technical Design Report", SDC-92-201 (1992)
- [2] Nitto Radcolor Film, A color film as a radiation dose indicator, Nitto Electric Industrial Co. Ltd.
- [3] T. Ohsugi *et al.*, Nucl. Instr. and Meth. A265(1988)105
M. Nakamura *et al.*, Nucl. Instr. and Meth. A270(1988)42
A. Van Ginneken *et al.*, FNAL-Note FN-522 (1989)
- [4] P. Holl *et al.*, Nucl. Instr. and Meth. A257(1987)587
- [5] H. Zlok *et al.*, Private communication, Talk on this symposium
Zheng Li, Talk on this symposium
E. Fretwurst *et al.*, Talk on this symposium
R. Wheadon *et al.*, Talk on this symposium
- [6] Pitzl *et al.*, Nucl. Instr. and Meth. A311(1992)98

Figure Captions

Fig. 1: Structure at the p-side and n-side

Fig. 2: Schematic view of the set-up of the beam-irradiation test

Fig. 3: Dose dependence of the leakage current
Temperature = 20 °C, $V_{bias} = 140$ V

Fig. 4: Radiation effect of the polysilicon bias resistor
The voltage drop across the polysilicon resistor is divided by the leakage current so as to compensate for an increase in the leakage current due to irradiation. The sensor is a PSS at $V_{bias} = 80$ V

Fig. 5: Interstrip resistance as a function of the bias voltage
The resistance is normalized by the value at $V_{bias} = 120$ V
+ = 10 kGy, × = 20 kGy, ◇ = 40 kGy

Fig. 6: Elapsed time dependence of the depletion voltage of "Warm" and "Cold" sensors
+ = 10 kGy, ◇ = 40 kGy; Solid = "Cold", Dashed = "Warm"

Fig. 7: Schematic figure of the LED measurement

Fig. 8: a: Pulse heights for a non-irradiated $DSSS$ measured with LED (Normalized by the pulse height at $V_{bias} = 90$ V)
+ = 1150 nm, × = 850 nm
b: Pulse heights for a irradiated, 20 kGy, $DSSS$ measured with LED (Normalized by the pulse height at $V_{bias} = 90$ V)
+ = 1150 nm, × = 850 nm

Fig. 9: Bias voltage dependence of the pulse height for both irradiated and non-irradiated sensors measured with β -rays
+ = Irradiated (20 kGy), measured at 10 °C
◇ = Non-irradiated, measured at 20 °C

Fig. 1a

Fig. 1b

Fig. 2

Fig. 3

Voltage Drop(mV)/Dose(kGy)

Fig. 4

Interstrip Resistance (MΩ)

Fig. 5

Fig. 6

Fig. 7

Pulse Height
(Normalized)

Fig. 8a

Pulse Height
(Normalized)