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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Double-sided microstrip sensor for the barrel of the SDC silicon tracker

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A full-size prototype microstrip sensor for the silicon tracker of the SDC detector to be used at the Superconducting Super Collider has been fabricated at Hamamatsu Photonics. The sensor is double-sided, using an AC-coupled readout with 50 μm pitch strips. The sensor size is 3.4×6.0 cm^2. Polycrystalline silicon is used as a bias feeding resistor on both surfaces. Each ohmic strip is isolated by a p^+ blocking line. The detailed requirements for the silicon tracker and the corresponding specifications as well as how to achieve them are discussed. The static performances of this prototype sensor are presented.

1. Introduction

Forthcoming high energy physics experiments with high-intensity beams require detectors which have a high spatial resolution, high-speed response, excellent two-track separation and adequate radiation hardness for the tracking device to be placed near the interaction point. A silicon microstrip detector is one of the most promising candidates for such a detector. Although the radiation damage effects in the bulk of the silicon detector have gradually been clarified [1], those in the surface are still not well understood. In this sense, no design standard for a radiation-hard microstrip sensor has yet been established, particularly for a double-sided, AC-coupled sensor. A device of this type has great advantages for reducing the material thickness of the silicon tracking detector. A reduction of the material thickness is of essential importance for electron tracking and momentum measurements, since it minimizes the energy loss due to bremsstrahlung radiation and improves the accurate tracking of low-energy particles, due to reduced multiple scattering.

We are attempting to optimize the design of the silicon microstrip sensor for the SDC barrel tracking detector [2] in the SSC experiment. We chose a digital readout scheme in order to simplify the readout electronics, because there are a total of 6 million readout channels in the SDC silicon tracker. The sensor design should therefore be optimized for the digital readout scheme.

Radiation hardness is the most crucial requirement for the SDC microstrip sensor. We have set the design goal that the detector be operational up to a radiation level of 10^{14} protons/cm^2. Such a level of irradiation causes a change in the effective donor or acceptor concentrations, so that the full depletion voltage of the 300 μm-thick sensor increases to 180 V [3]. The sensor should accordingly be usable at more than a 200 V bias without any breakdown. This requirement is rather

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difficult to meet because the breakdown voltage for the usual type of semiconductor devices is of the order of a few tens of volts.

The signal-to-noise ratio is targeted to be 18 to 1 for the average energy loss of the minimum ionizing particles. This can be achieved only with a small readout capacitance for a fast preamplifier readout used for SSC experiments [4].

To keep the timing within 16 ns of the SSC beam crossing interval, a series resistance for the electrode may also be a non-trivial parameter. All of these requirements determine the specifications of this prototype sensor.

2. Sensor specification

The specifications of the prototype sensor are presented in Table 1 in which each individual value listed is a target to be achieved. The size is chosen so that the common readout area of both sides matches to 640 readout channels and two sensors are produced from a 4-in. wafer. Since a digital readout scheme (reading out only on-off signals from each strip) is employed for the SDC detector, a readout strip pitch of 50 μm is the optimum value to attain a good spatial resolution as well as a small interstrip capacitance. The spatial resolution observed from the combination of this sensor and the digital readout system has been reported elsewhere [5].

A substrate resistivity of more than 4 kΩ cm for a 300 μm thick sensor in which the full depletion voltage is expected to be less than 80 V is adequate for our purpose. The type inversion of the bulk takes place by irradiation of a few times 10^{13} protons/cm^2. Then, the full depletion voltage increases to 130 V at a fluence of 5×10^{13} protons/cm^2 [3]. After irradiation of 5×10^{13} protons/cm^2, the depletion voltage is independent of the initial resistivity [3], since the effective doping concentration is dominated by the acceptor-like defects induced by the irradiation.

The bias resistor is implemented at one end of each strip with polycrystalline silicon (poly-Si). Its resistance is chosen to be 250 kΩ so that the large leakage current after irradiation does not affect the bias potential distribution by a significant potential drop at the bias resistor. In our case a resistance of more than 200 kΩ (2 μs time constant with a 10 pF detector capacitance) is sufficiently large to collect the signal with the readout electronics using a 20 ns shaping time [4].

The n^+ strip isolation is achieved with a p^+ blocking line completely surrounding each n^+ strip, as shown in Fig. 1. Since the p^+ blocking line is not connected to any electrode, the channel is floating. The boron was implanted with a concentration of 5×10^{13}/cm^2 in the p^+ blocking line because the radiation hardness of the isolation with this concentration had been confirmed up to 40 kGy by proton irradiation in our previous experiment [6].

Table 1
Specifications of the prototype sensor for the SDC barrel silicon tracker

Dimensions	
Outer size	34.1 mm × 60.0 mm
Sensitive area	32.6 mm × 58.8 mm
Readout pitch	50 μm
Readout channels	654 (axial), 668 (stereo)
Substrate (n-type)	
Thickness	300 ± 10 μm
Resistivity	4–8 kΩ cm
Bias resistor	
Installation area	200 μm × 40 μm
Junction side	poly-Si, 250 ± 30 kΩ
Ohmic side	poly-Si, 250 ± 30 kΩ
Strip structure	
Axial strip	implemented on the ohmic-strip side 12 μm wide
Stereo-strip	implemented on the junction-strip side 12 μm wide, 10 mrad tilted
Isolation method	
Ohmic side	p^+ blocking line surrounding n^+ ohmic strip 26 μm wide
Coupling capacitor and readout electrode	
Coupling material	SiO_2
Coupling capacitance	20 pF/cm
Interstrip capacitance	1.05 pF/cm (junction-strip side)
Al electrode	1.20 pF/cm (ohmic-strip side) 6 μm wide, 40 Ω/cm
Balance resistor	poly-Si, 80 MΩ × 2
Bonding pad	50 μm × 150 μm, Two column staggered, 200 μm apart
Guard ring	Underneath of bias ring, 20 μm wide, single
Passivation	SiO_2 covering entire sensor except bonding pad
Miscellaneous	
Fiducial mark	16 marks along the edges and corners
Strip counting mark	Every 10 strips, every 100 strip
Dicing saw, cutting zone	± 30 μm for full cutting

The axial strip is implemented on the ohmic-strip side in order to optimize the performance in momentum measurements even after irradiation, since liberated electrons are collected to form a signal on the n^+ strip much faster than on the p^+ strip where holes are collected. In addition, the bulk type inversion after a certain amount of irradiation, which moves the p–n junction from the p^+ strip side to the n^+ strip side, gives a capacitance of the n^+ strips lower than that of the p^+ strips [7].

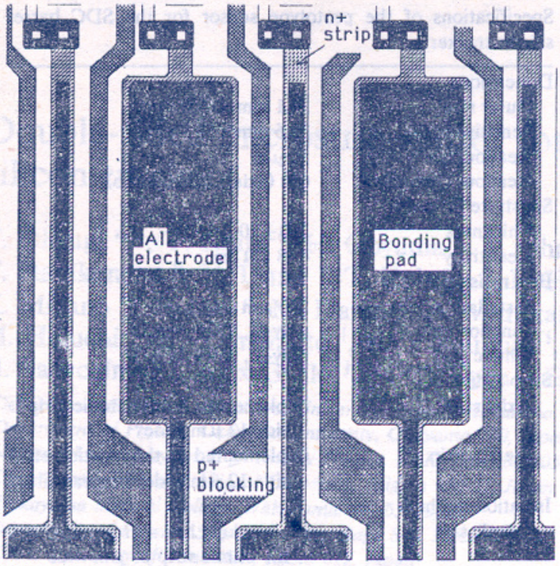

Fig. 1. Schematic picture of n-side isolation by a surrounding p^+ blocking line.

The strip width on either surface is chosen to be as narrow as possible, while the p^+ blocking line is designed to be as wide as possible so as to reduce the interstrip capacitance [7,8]. The minimum gap (including some safety margin) to prevent breakdown between implanted channels has been found to be 5 μm. We choose a 6 μm wide external electrode to reduce the interstrip capacitance. The 6 μm wide external electrode on a 12 μm wide implanted strip has a sufficient margin to avoid any edge avalanche due to the MOS effect [9].

The layout of strips, bias resistors, guard ring, bonding pads and fiducial marks are shown in Fig. 2. A pair of balance resistors (80 MΩ) has been installed along the outside of the bias ring to form a potential divider for defining the ground potential between the preamplifiers for the p^+ strip and the n^+ strip. In this prototype sensor, the bonding pads are installed only on the AC-coupled electrode. No bonding pad or test-probe-pad connected directly to the implant has been installed. The stereo angle for the strips on the junction side was chosen to be 10 mrad relative to the axial strips [2].

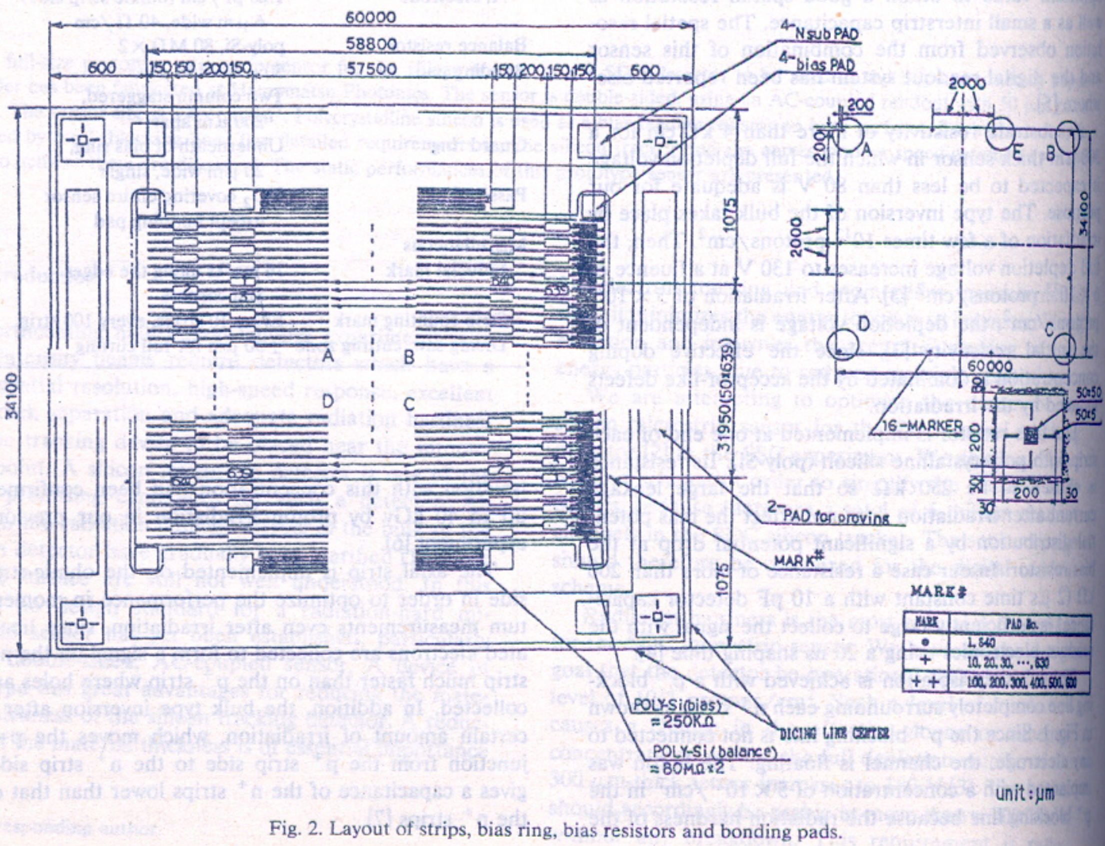

Fig. 2. Layout of strips, bias ring, bias resistors and bonding pads.

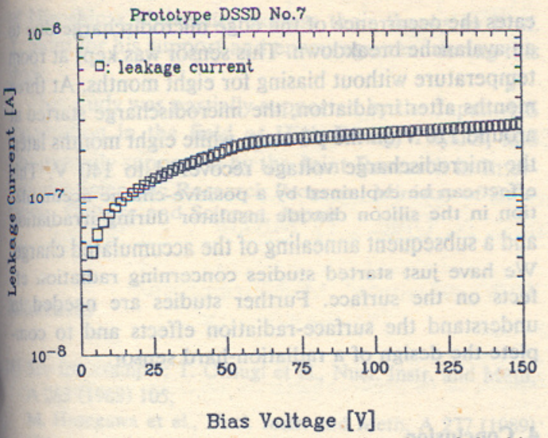

Fig. 3. Leakage current measured as a function of the bias voltage.

As shown in Fig. 2, fiducial marks for alignment are on each corner and on the center of each side edge. Three marks are printed 2 mm apart at the center of the side edge to locate the position and direction easily by microscope. Their position accuracy is ± 1 μm.

3. Results and discussions

Twenty samples have been fabricated for various tests, including beam experiments. The production yield of the coupling capacitors on the p^+ strip was excellent, while that of the capacitors on the n^+ strip had some problems. A few percent of the capacitors were short-circuited due to pinholes. One possible reason is that the surface may have been scratched during processing of the opposite side. This may be the reason that a single-sided sensor has almost a perfect yield of capacitors. A detailed investigation of this problem is continuing at Hamamatsu Photonics Company.

Leakage current. The initial leakage currents of 19 cm^2 sensors are in the range from 400 to 600 nA. The bias-voltage dependence shows a clear plateau up to 150 V in the case of a reverse-biased diode, as shown in Fig 3. This sensor has a single bias/guard ring structure.

Full depletion voltage. The full depletion voltage (V_{dep}) was measured by a technique of locating the bias voltage which gives the minimum body capacitance. The values of V_{dep} are in the range of 50–80 V which are consistent with a bulk resistivity of 4–6 kΩ · cm. In our case, a full depletion voltage of less than 80 V is sufficiently good, as already mentioned.

Bias resistor. The S-shape poly-Si resistors of 6 μm width were implemented in a 200 μm space at one side edge of the strips. Their resistance values were measured to be 245 ± 5 kΩ and 275 ± 15 kΩ for the p^+ strips and the n^+ strips, respectively.

Resistance of the external Al-electrode. The resistance of the external Al-electrode was not negligibly small, since the Al electrode was only 6 μm wide and 1 μm thick. We used Al–Si alloy (0.3% Si) rather than pure Al. We were concerned that pure Al might cause spiking, which could degrade the breakdown voltage or the integrated capacitor. The DC resistance of the Al electrode was measured to be 70 ± 5 Ω/cm. This is 50% higher than the value expected from pure Al and is more than twice as large as the target one. To reduce the resistance, we must use pure Al and make a thicker Al electrode. We must then cope with the spiking problem. One possible solution is that a thin film of a more stable material, such as silicon nitride, is employed between silicon dioxide and a pure Al electrode.

Interstrip capacitance. To obtain a good signal-to-noise ratio, the amount of readout capacitance should be made as small as possible. An average signal charge deposition for a minimum ionizing particle with 300 μm path is expected to be 24 000 electrons. The noise charge is estimated to be 1300 equivalent noise charges (ENC) by assuming a 12 cm long strip having a 1.2 pF/cm readout capacitance and a preamplifier designed for the SDC [2]. The body capacitance of the entire sensor chip (19 $cm^2 \times 300$ μm) was measured to be 0.60 ± 0.05 nF with a 90 V bias at a frequency of 100 kHz. The corresponding body capacitance per strip per cm is 0.15 ± 0.20 pF/cm. Thus, the target for the interstrip capacitance of our sensor is ≤ 1.05 pF/cm. Fig. 4 shows the bias-voltage dependence of the interstrip capacitance between a strip and its two adjacent strips at a frequency of 100 kHz. The full-depletion voltage of this sample was 75 V. The measured values of the interstrip capacitance with a 90 V bias at a

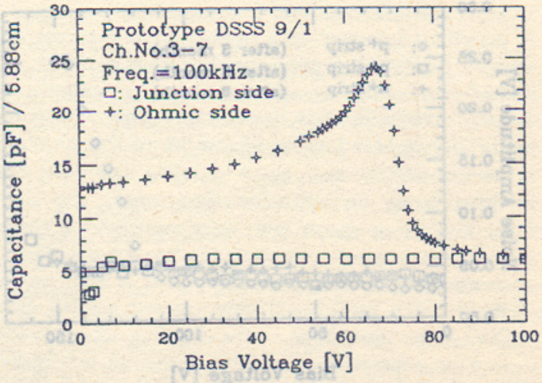

Fig. 4. Bias-voltage dependence of the interstrip capacitance at a frequency of 100 kHz. The full depletion voltage of this sample is found to be 75 V.

frequency of 100 kHz are 1.0 ± 0.1 and 1.2 ± 0.1 pF/cm for the p^+ strip side and the n^+ strip side, respectively. These capacitance values are sufficiently close to the target values. The errors attached to the capacitance are due to samplewise fluctuation.

Coupling capacitance. The coupling capacitance of the integrated capacitor should be more than 20 pF/cm in order to obtain an 18-to-1 ratio of the coupling to the interstrip capacitance and to maintain a signal cross-talk of less than 6%. The value obtained with this prototype was 13 pF/cm with a 0.2 μm thick silicon dioxide insulator, which is 30% less than the specification value. A wider external electrode, a better coupling material and a better coupling film structure should be studied so as to increase the coupling capacitance as well as to improve any breakdown problems caused by pinholes. We plan to study a double-layer structure with silicon dioxide and silicon nitride to eliminate pinholes without decreasing the coupling capacitance.

Edge micro-discharge. The threshold voltage of a microdischarge at the strip edge due to the MOS effect is a critical parameter of the AC-coupled, double-sided sensor [9]. An external electrode of 6 μm width combined with an implanted strip of 12 μm width has successfully solved the microdischarge problem due to the MOS effect. No microdischarge has been observed up to 150 V for the p^+ strip. We have exposed this sample to an 800 MeV proton beam in order to investigate the radiation effect upon the occurrence of the microdischarge. Fig. 5 shows the bias-voltage dependence of the noise amplitude after proton irradiation of $10^{14}/cm^2$. During the irradiation a bias voltage of 70 V was applied to the sensor. The steep increase indicates the occurrence of the edge microdischarge due to an avalanche breakdown. This sensor was kept at room temperature without biasing for eight months. At three months after irradiation, the microdischarge started at around 110 V on the p^+ strip, while eight months later, the microdischarge voltage recovered to 140 V. This effect can be explained by a positive-charge accumulation in the silicon dioxide insulator during irradiation and a subsequent annealing of the accumulated charge. We have just started studies concerning radiation effects on the surface. Further studies are needed to understand the surface-radiation effects and to complete the design of a radiation-hard sensor.

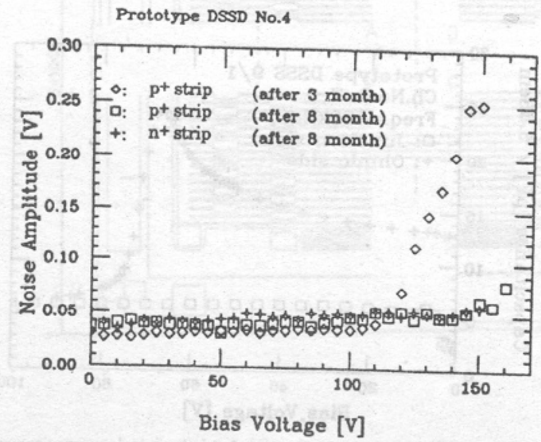

Fig. 5. Rms amplitude of the noise measured as a function of bias voltage when three and eight months has passed after an irradiation of 10^{14} protons/cm^2.

4. Conclusion

A full-size prototype sensor for the SDC experiment has been successfully fabricated at Hamamatsu Photonics. It is based on knowledge obtained from a series of earlier sensor studies. The prototype sensor uses an AC-coupled, double-sided and small-angle stereo strip design with a size of 3.4×6.0 cm^2. The methods of bias feeding and the ohmic-strip isolations have been established by using a poly-Si resistor and a p^+ blocking line, respectively. The leakage currents are around 0.5 μA for sensors of 19 cm^2 sensitive area. Although the junction-side capacitor had an excellent production yield, the yield of the ohmic-strip side capacitor had some problems. The geometry of the implanted strips and the external readout electrodes was chosen so as to optimize the following three contradictory requirements: a small interstrip capacitance, a large coupling capacitance of the external readout electrode to the implanted strip and a sufficiently large operating margin before the onset of the edge microdischarge problem. The measured values of the interstrip capacitance of the prototype sensor are 1.0 and 1.2 pF/cm for the p^+ strip and the n^+ strip, respectively. The coupling capacitance is 13 pF/cm, which is 30% less than the target value. A design rule of the integrated capacitor of the AC-coupled readout to avoid the microdischarge has been applied and its validity confirmed. However, the radiation effects of the edge microdischarge have not yet been fully understood. A systematic study of the radiation effects on the edge microdischarge is being planned in the near future.

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