Development and Test of Silicon Strip Detector for International Linear Collider

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1. Introduction

The international linear collider (ILC) project [1] is being pursued to search Higgs and new particles beyond Standard Model (SM). To achieve physics purpose three major detector concepts (Global Large Detector, Large Detector Concept, Silicon Detector) are being considered. The silicon strip detectors will be used for tracking of charged particles in all of detector concepts. In general, silicon strip detectors are placed closer to the interaction points than some other detector (for example. main trackers and calorimeters) to determine the vertices and/or trajectories of the particle produced from the interaction of the accelerated particles.

The silicon strip detector between the silicon vertex detector and the Time Projection Chamber (TPC) in the Global Large Detector (GLD) concept will be located to improve linking efficiency and track reconstruction, and is called as the intermediate tracker (IMT). The IMT has 4 layers of 380 μm thick silicon sensors located at 9 cm, 16 cm, 23 cm and 30 cm radially. It covers the $|\cos\theta| < 0.9$ region, and the required spatial $r\phi$ resolution is $\sigma_{r\phi} < 40$ μm. Fig. 1 shows the IMT at GLD in the ILC. We have designed and developed the DC/AC-coupled double-sided and single-sided silicon strip sensors for the IMT in the international linear collider experiment.

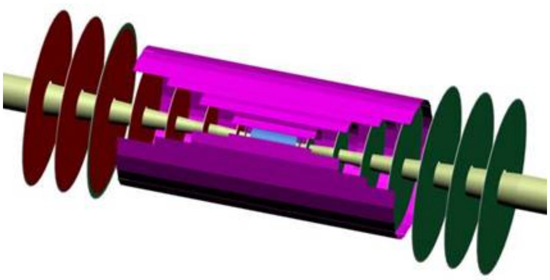
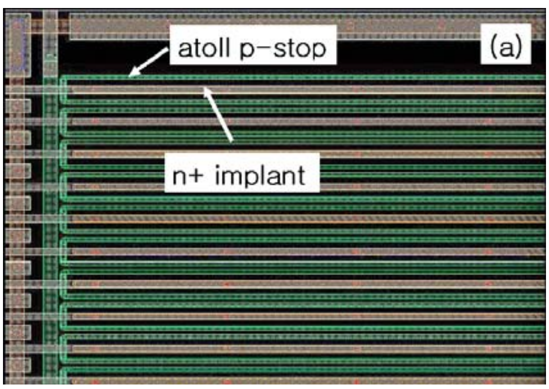


Fig. 1. Intermediate tracker (IMT) at Global Large Detector (GLD) concept in the international linear collider and the silicon vertex detector inside the IMT is shown in blue color. The barrel and endcap of the IMT consist of 4 and 7 layers of silicon detector.

The electrical characteristics of the fabricated strip sensors are measured as a function of the reverse bias voltages. A comparison of the leakage current, the depletion voltage, the signal, and the noise of the silicon strip sensors before and after irradiation is a practical means of studying the radiation hardness of the sensors. In the paper we present a comparison of the leakage current alone before and after irradiation as study of the radiation hardness of silicon sensors. The radiation damage test is performed with 35 MeV proton beam from the MC-50 cyclotron at the Korea Institute of Radiological and Medical Science (KIRAMS) and we compared the leakage current of the sensors before and after silicon sensors are irradiated by the proton beam. We also perform sensor test with ^{90}Sr radioactive source and measure the signal-to-noise ratio of the silicon sensors.

2. Design and Fabrication

We used high resistivity (100) n-type double-sided polished silicon wafer of 380 μm thickness. Five and six photomasks were used for the fabrication of the n-side and p-side of the double-sided silicon strip sensor, respectively. The p-stops in an atoll pattern to prevent electrical shortening due to the electron accumulation layer on the n-side are designed and fabricated as shown in Fig. 2(a). The direction of the p-strips is orthogonal to that of the n-strips but the direction of the signal readout strips of the p-side is the same of those of the n-side to make both material budget and electronics space less. This requires a double-metal structure on the p-side and it is shown in Fig. 2(b). A very thick oxidation layer is deposited between the first metal and second metal to ensure electrical insulation. The first metal and the second metal are electrically connected by via-hole process.



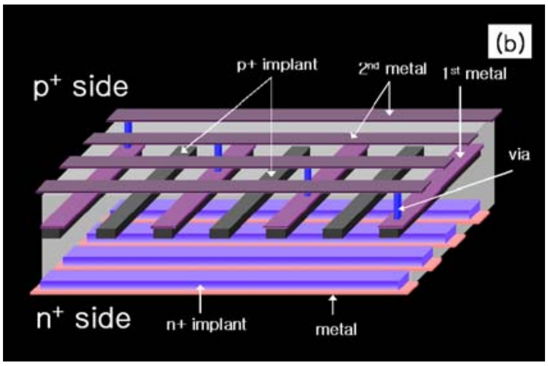


Fig. 2. Layouts of the DC-coupled double-sided silicon strip sensors: (a) The n+ implant strips and the p-stops in atoll pattern (b) The double-metal structures on the p+ side (the p-stops on the n+ side are omitted for clarity).

A total of 5 photomasks were used to fabricate the single-sided silicon strip sensors. The DC- and AC-coupled single-sided strip sensor are fabricated on the same wafer to maximize efficiency of the bare wafer. The fabrication process for DC-coupled single-sided silicon strip sensors is almost same as that for DC-coupled double-sided silicon strip sensors. Since there is no implantation process needed in the n-side except for the ohmic contact, the fabrication steps for the single-sided silicon strip sensor are much simple compared with the double-sided. But the biasing resistors and coupling capacitors are designed and fabricated for the AC-coupled sensors and are shown in Fig. 3.

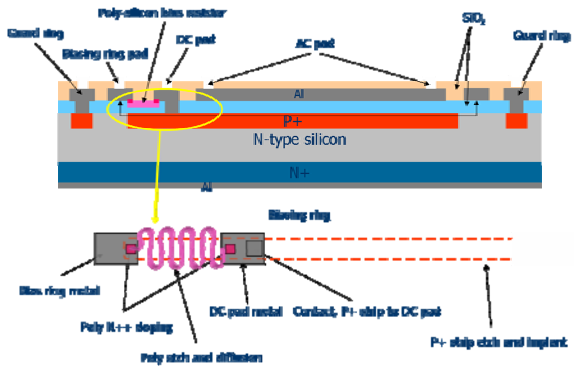


Fig. 3. Cross sectional view of the AC-coupled single-sided strip sensor having the polysilicon biasing resistors and the coupling capacitor. The thickness of the oxide layer, the length and the width of p-doped polysilicon are optimized to make capacitance we target, respectively.

In the AC-coupled silicon strip sensor we integrated high ohmic resistors and large capacitors into the silicon sensor. The coupling capacitor for each strip is constructed by interleaving a thin oxide layer between implantation and metallization. The resistance of the biasing resistor can be determined by changing the length and widths of polysilicon.

The specifications of the prototype sensors we developed are summarized in Table 1.

Table 1. Specification of prototype silicon strip sensors.

Wafer		
Doping	n-type	
Orientation	(1 0 0)	
Size	5-inches	
Bulk resistivity (kΩcm)	>5	
Thickness (μm)	380 μm	
Double-sided Silicon Strip Detector		
Area(μm^2)	55610 × 29460	
Effective area(μm^2)	51072 × 25550	
	p^+ side	n^+ side
Number of strips	511	511
Strip pitch (μm)	100	50
Readout trace pitch	50	50
Strip length (μm)	25600	51072
Strip width (μm)	9	9
AC-coupled Single-sided Silicon Strip Detector		
Area (μm^2)	35000 × 35000	
Effective area (μm^2)	31970 × 31970	
Number of strips	64	
Strip pitch (μm)	500	
	Type1	Typep2
Strip width (implant) (μm)	200	300
Strip width (Al) (μm)	220	320
SiO_2 layer thickness (μm)	1	1
Polysilicon length (μm)	10	10
Polysilicon width (μm)	13500	13500

3. Electrical test

Since the leakage current is a direct check of the fabrication quality, the leakage currents of the developed double-sided and single-sided silicon strip sensor are measured with Keithley 6517 picoammeter. The capacitances as a function of the reverse bias voltages are measured with HP 4277A LCZ meter. The results showed that the leakage currents were measured to be less than 10 nA/strip as shown in Fig. 4.

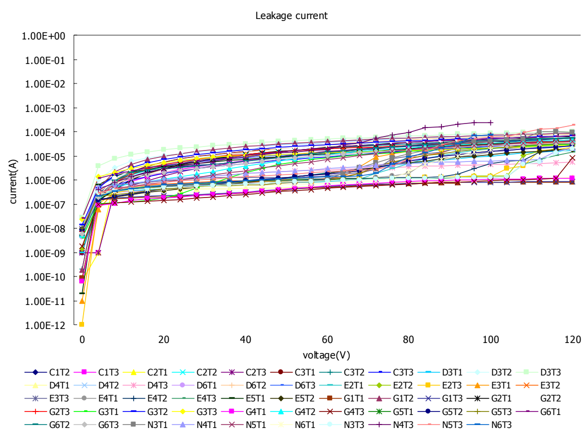


Fig. 4. The leakage current distribution as a function of the reverse bias voltages for different double-sided strip sensors. Each color represents a double-sided strip sensors of a size of 55610 × 29460 μm^2 with 512 readout channels on each side.

The information of the depletion voltage is obtained from the capacitances distribution and the measurement results of the capacitances showed were as we expected from the resistivity and thickness of the silicon sensors. The capacitances as a function of the reverse bias voltages are shown in Fig. 5.

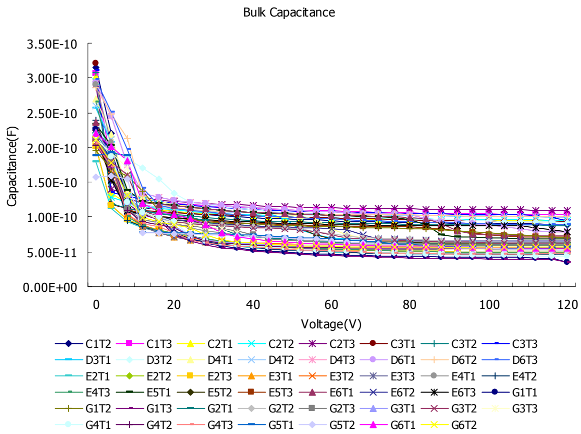


Fig. 5. The bias voltage dependence of the sensor bulk capacitances.

For AC-coupled strip sensors, the DC-pads were designed to measure the leakage currents and polysilicon resistance as shown in Fig 6.

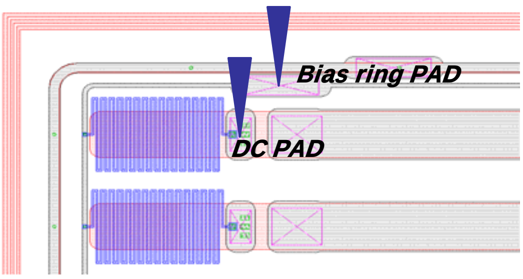


Fig. 6. Layout of AC-coupled strip sensor and probing bais ring pad and DC pad for measurement of resistance of polysilicon.

Fig. 7 shows the measured resistance of the biasing resistor by varying reverse bias voltages and the results show the value of the resistance is obtained as we target and is stable up to the depletion voltage.

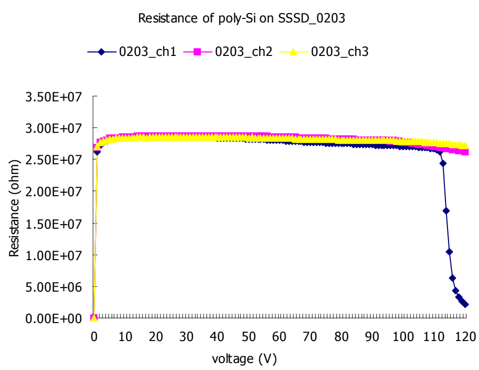


Fig. 7. The resistances of the biasing resistor are measured by varying the reverse bias voltages above the operation voltage.

The coupling capacitances of the AC-coupled single-sided strip sensors are measured and a way of the measurement and the measurement results are shown in Fig. 8. and Fig. 9, respectively.

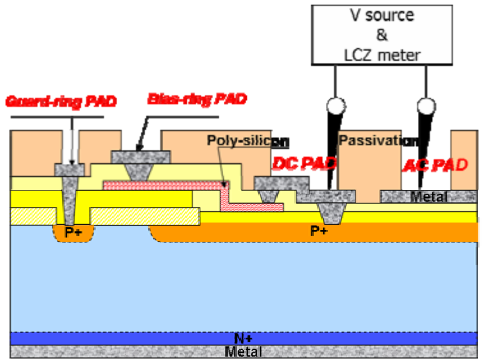


Fig. 8. A cross sectional view of the AC-coupled single-sided silicon strip detector and measurement method of coupling capacitance of the sensors.

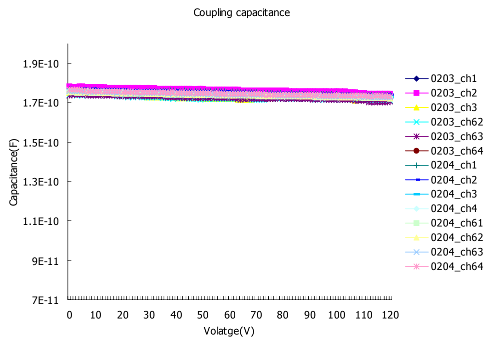


Fig. 9. The capacitances of the AC-coupled single-sided silicon strip sensor as a function of the reverse bias voltages above the operation voltage.

Both measured resistances and the capacitances of arbitrary selected channels of the AC-coupled single-sided strip sensors are listed in Table 2 for different strip types.

Table 2. Measurement results of the resistances of the biasing resistors and coupling capacitances of the AC-coupled single-sided strip sensors.

sensor ID	0101			
	AC1		AC2	
	C_c (pF)	R_bias(MΩ)	C_c (pF)	R_bias(MΩ)
ch.1	178	25.4	251	24.2
ch.2	175	25.5	260	24.0
ch.63	169	27.0	257	20.6
ch.64	177	26.7	261	20.8
AVE	174.75	26.15	257.25	22.4

4. Radiation Damage and Beta source test

Since the silicon strip detectors are exposed to higher radiation doses and are susceptible to radiation damage, it is important for the silicon strip sensors to have the appropriate radiation hardness. As a reference for the radiation dose on the inner detectors in the ILC, TESLA

(TeV-Energy Superconducting Linear Accelerator) estimates [2] the dominant e^+e^- pair background (that falls rapidly as the radial distance increases) from the beam-beam interaction to be 100 kRad for a 5 year period in the region between radii of 1.5 cm and 6 cm from the interaction point. TESLA also estimates the neutron background to be 10^9 1-MeV equivalent neutron $/cm^2$/year in the same radial region. The radiation dose of 100 kRad of electrons and positrons is not particularly worrisome because modern silicon devices are known to be able to withstand that radiation dose of electrons and positrons. However, the neutron radiation is potentially more serious than the electron and positron radiation, especially in the silicon bulk, because the non-ionizing energy loss (NIEL) of neutrons may produce a cascade of further displacements following the primary displacement of a knock-on silicon atom while the ionizing energy loss of electrons or positrons does not produce any atomic displacements [3][4].

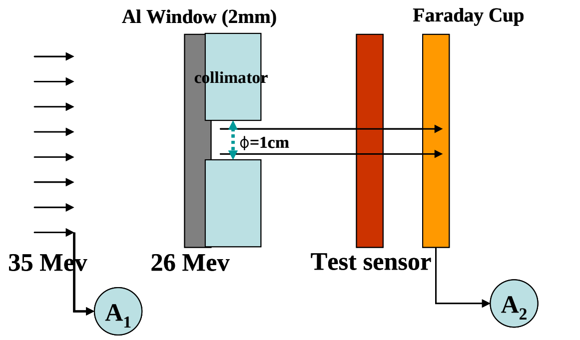


Fig. 10. Setup for the proton beam irradiation. The currents of both the incoming (A1) and the outgoing (A2) proton beams are monitored using Faraday cups.

With respect to radiation damage with the prototype we used 35 MeV proton beam of a cyclotron in Korea Institute of Radiological and Medical Science in Seoul [5], Korea. The experimental setup for the proton irradiation using the proton beam is shown in Fig.10. The irradiation was performed at the room temperature, and bias was applied to the sensor during the irradiation. The 35 MeV incoming proton beam passes through a 0.2 cm thick aluminum window capping the beam pipe and loses its energy down to 26 MeV. The proton beam is then collimated to an 1 cm diameter beam spot by using a carbon collimator. The currents of both incoming and outgoing proton beams are monitored using Faraday cups to ensure that number of protons we target for exactly irradiate the silicon strip sensors. The range of the proton beam fluxes are from 10^{12} to 10^{15} number of proton/cm^2 and the overall leakage current of the double-sided silicon strip sensors are shown in Fig. 11 (a), (b), (c), and (d) [6]. Shown in diamonds, triangles and rectangles are the currents before, one day after, and 39 days after the irradiation for each sensor. The prototypes have been operated up to a few times of 10^{12} number of proton/cm^2 with negligible effect of increase of leakage current. From the test results of proton beam irradiation, we concluded that developed sensors have an excellent safety margin of radiation hardness appropriate for the ILC.

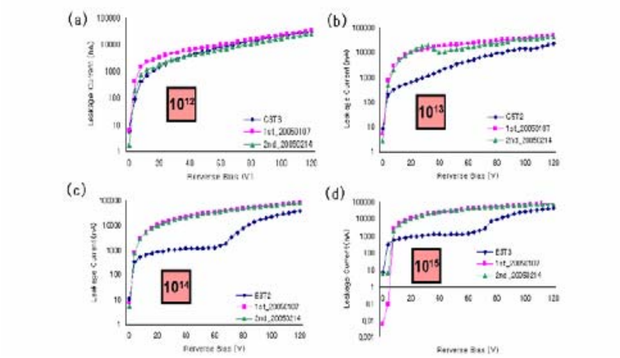


Fig. 11. Overall leakage current as a function of the reverse bias voltage for four silicon strip sensors irradiated with the four different numbers of protons cm−2 shown in the boxes. Diamonds, triangles and rectangles represents the current values before, one day after, and 39 days after the irradiation.

We also measured the signal-to-noise ratio (SNR) of the silicon strip sensor with the ^{90}Sr radioactive source and the experimental setup for the SNR measurement is shown in Fig. 12. A photodiode sensor of Hamamatsu Photonics was used for the trigger purpose. An analog signal from the silicon sensor was connected into the analog input of the FADC board via a preamplifier and an amplifier. A signal from the trigger sensor was connected into the trigger input of the FADC board via a preamplifier, an amplifier and a discriminator. An FADC output was recorded into the personal computer and data was analyzed with C++ based data analysis program.

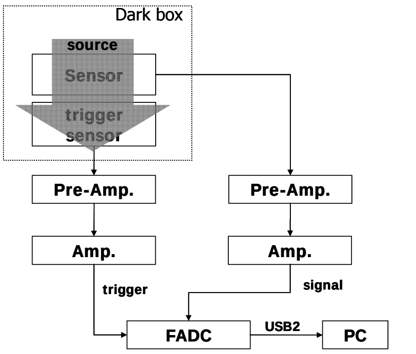


Fig.12. Experiment setup for the signal-to-noise ratio measurement.

As shown in Fig. 13 the result showed that the SNR of the strip sensor is as good as 25.0. The S/N ratio measurement with the proton beam in KIRAMS is scheduled before the end of this year.

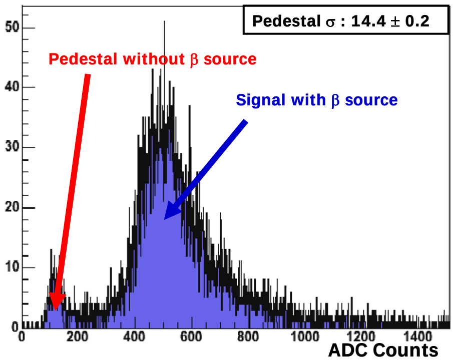


Fig.13. The measurement result of the signal-to-noise ratio with the ^{90}Sr beta source.

4. Results and Discussion

Various types of silicon strip sensors such as DC-coupled and AC-coupled double-sided and single-sided with different strip pitches are designed and fabricated for R&D purpose to be used in the silicon tracker at international linear collider experiment. These strip sensors are fabricated on high resistivity (100) n-type double-sided polished silicon wafer of 380 μm thickness. To protect any damages during fabrication process the silicon nitride is used just after oxidation process. Due to different temperature dependence of Si_3N_4 and SiO_2 the thicknesses of the Si_3N_4 and the SiO_2 layers are optimized from the process simulation (ATLAS) results to avoid cracks.

Our prototype silicon strip sensors typically exhibit the full depletion voltage of about 60 V, which is consistent with the specification for the resistivity (> 9 kΩcm) of the bare silicon wafers on which our sensors are fabricated. In real operations of silicon detectors in high energy physics experiment the over-depletion voltage is a common practice to insure of full depletion of the silicon sensor and avoid any inadvertent voltage drop that might cause undesirable under depletion of the silicon sensors. The measurement shows that the leakage current of the sensor is less than 10 nA/channel.

A negligible of the leakage currents are measured for the irradiated sensor with 1012 proton/cm2 during a period of 39 days after the irradiation but a large increase (at least a 131%) in the leakage current is observed for the three irradiated sensors with 1013 proton/cm2 or more. The overall leakage currents of these three sensors are decreased at 30 days later and it indicates an annealing effect on the leakage current [7]. The results of proton beam irradiation show that developed silicon strip sensors have an excellent safety margin of radiation hardness appropriate not only for the intermediate trackers in the GLD configuration, but also for trackers in the other detector concepts for the international linear collider experiment.

We also measured the signal-to-noise ratio of the developed sensor to be about 25.0 with beta radioactive source.

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REFERENCES

[1] http://www.linearcollider.org
[2] T. Behnke, S. Bertolucci, R. D. Heuer and R. Settles, TESLA (TeV-Energy Superconducting Linear Accelerator) Technical Design Report PART IV, A Detector for TESLA, 2001
[3] G. Lutz, Semiconductor Radiation Detectors (Springer-Verlag, Berlin, 1999), p.275
[4] A. Vasilescu and G. Lindstrom, ROSE/TN/2000-02. Rose Technical Note, June, 2000. (http://rd48.web.cern.ch/RD48/technical-notes/rosetn.htm)
[5] Korea Institute of Radiological and Medical Science, Gongneung-dong, Nowon-gu, Seoul , Korea
[6] Jik Lee, et al., J. Korean Phys. Soc. 48, 850 (2006)
[7] G. Lindstrom, et al., Nucl. Instr. and Meth. A 466, 308 (2001)