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RADIATION DAMAGE TEST OF SILICON MICROSTRIP DETECTORS

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Summary

Radiation damage tests of newly developed silicon microstrip detectors were performed using 800 GeV proton beam. The leakage current increased proportional to the integrated beam intensity. No fatal damages such as breakdown are observed up to the integrated intensity exceeding $10^{14}/cm^2$. The peak of minimum ionizing particles is clearly seen for irradiated silicon detectors with leak current of as high as 1.4 μA/strip. There is no pulse height degradation. The bias voltage necessary for full depletion had to be raised from 20 V to 40 V for radiation damaged samples.

We observed a strong temperature dependence of leak current caused by the radiation damage. It is demonstrated that by cooling the detector to 7°C, we are able to reduce the leak current by factor 4. We demonstrated that the silicon detector could be made operational by moderate cooling even after irradiation much higher than $10^{14}/cm^2$.

Introduction

It is believed that the best candidate for a vertex detector for experiments at SSC is a silicon microstrip detector. It has been demonstrated by a few pioneering experiments done at CERN that, with silicon microstrip detectors, one is able to locate charged particle trajectories with a space resolution as low as 10 μm[1,2]. Besides, its intrinsic speed of charge collection is fast enough to complete within 30 nsec. This fast response as well as its high spatial resolution are the most attractive points in particular for high rate and high multiplicity enviroments such as SSC. Obviously there are many technical problems to be solved by extensive R and D efforts before we use silicon microstrip detectors as a vertex detector for colliding beam experiments. One of problems to be solved is radiation damage of silicon detectors and associated electronics. Some tests has been done for radiation damage of silicon detectors[3,4], though there are few systematic studies and analysis of damages so far.

We present our preliminary results of radiation damage tests of silicon microstrip detectors that are newly fabricated for test production[5].

Table I. Basic properties of the silicon detector

material	∼10kΩ*cm n-doped silicon crystal
size	30 mm * 30 mm, 200 μm in thickness
strip pitch	500 μm
strip width	385 μm
strip length	28.4 mm
bonding pad	200 μm * 385 μm
full depletion	20 V
leak current	2 nA/strip at 25°C, 50 V
breakdown	∼ 500 V

Basic Properties

We summarize below some properties of silicon microstrip detectors used for the present test. The surface of the detector is protected with a thin epoxy coat. The silicon detector is glued onto a fiber glass printed board. Connections are made with 30 μm diameter Al wires, using an ultrasonic bonding method. The wire bonds are covered with an epoxy resin for protection.
The basic performance of the detector was checked using cosmic rays, ^{241}Am sources(59.5 keV γ and $^{90}Sr/^{90}Y$ sources(2.26 MeV collimated β). For penetrating β-rays, triggers were generated by a sintillator situated behind the silicon detector. Signals are amplified by a LeCroy HQV810 charge amplifier with a subsequent shaping circuit of 250 nsec. The output charge is measured by a qVt(LeCroy 3100) with an external gate width of 500 nsec. Fig.1 is the pulse height spectrum for penetrating β-rays at the reverse bias voltage of 20 V. In Fig.2 the signal height is plotted as a function of bias voltage, showing the full depletion at 20 V.

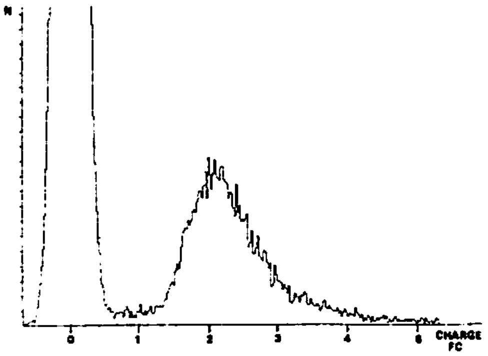

Fig.1 Pulse height distribution of penetrating β-rays from a non-damaged strip. Data are taken at V_b=20 V and 23.0°C.

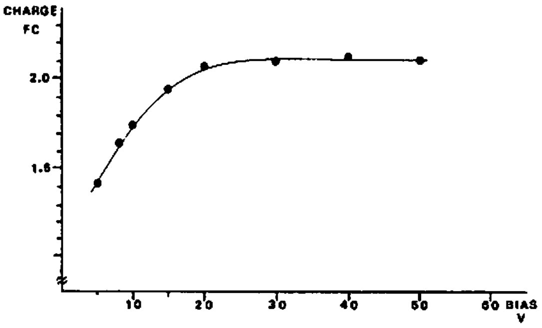

Fig.2 Pulse height dependence of penetrating β-rays on bias voltage V_b at 23.2°C.

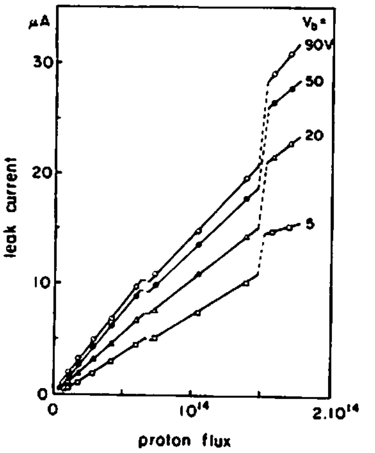

Fig.3 The combined leakage current of three strips at four different bias voltages as a function of integrated intensity of 800 GeV protons. There were changes of beam profiles three times during the exposure.

Irradiation by 800 GeV Protons

Test samples of our silicon microstrip detectors were exposed directly to the Fermilab 800 GeV primary proton beam in the enclosure NE8 in front of the target for the Neutrino Test beam. The beam is normal to the silicon strip plane. Thin copper foils were attached in order to monitor the integrated proton intensity using the foil activation method. Sheets of RADCOLOR film No.381[6] were also mounted to monitor the beam profile as well as total proton dose. During the exposure of protons, three strips were reverse biased at 20 V, while remaining 53 strips were kept in floating potential. The combined leak current of these three reverse-biased strips (No.25, 27 and 29) were frequently monitored at four different bias voltages during the exposure as shown in Fig.3. Unfortunately the beam profiles were changed three times during the exposure as is indicated in the figure. When the beam profile stayed fixed, the leak current increased linearly with the integrated proton intensity. It is also noted that the leak current dependence on the bias voltage stayed constant. For example, the leak current ratio between V_b=90 V and 5 V seems to stay at around 2 from the beginning to the exposure end. Near the end of exposure, we got a very collimated beam on our silicon detector for a while. Our later examination revealed that $1.04*10^{13}$ protons had irradiated a spot of $0.7 * 3$ mm^2, corresponding to the local radiation density of $3.5*10^{14}$ protons/cm^2 or ~10 MRads.

About 12 hours after the exposure, the first measurement of leak current was performed up to the bias voltage of 90 V. We have observed no breakdown at 90 V. The leak current distribution seems to follow the beam profile recorded on the RADCOLOR film. No appreciable differences were observed in leakage between biased strips(No.25,27 and 29) and non-biased ones (other strips) during the exposure.

Performances of Damaged Detectors

(1) Leak Current: Fig.4 shows the total leak current as a function of bias voltage[7]. This second measurement of leakage current is performed 2 months after the exposure. Because of the strong temperature dependence of leak current, it is not easy to make any precise comparison between two leak current measuments 2 months apart. Approximately 45 % reduction in leak current is observed in which about 20 % is estimated to be due to the temperature difference. The rest (~25%) could be attributed to so-called room temperature curing[3]. Total proton intensity penetrated through the sensitive area is approximately $(1.3 \pm 0.2)*10^{14}$. This number is based on the total proton flux from the foil activation measurement with a 20 % correction due to the transverse beam spread. As is stated above, the leak current is proportional to accumulated radiation, namely fluence ϕ,

$$I_{leak} = I_0 + K\phi$$

where I_0 is the initial leakage before any exposures. Then we get, at V_b = 20 V,

$$k = 4.4*10^{-13}\ \mu\text{A/fluence}.$$

At this stage we have no idea whether the leak current observed comes from silicon surface or its bulk part. If we assume all from the bulk part, we get normalized influence of

$$k = 200\ \mu\text{A/cm}^3/10^{13}\ \text{fluence}.$$

This can be compared with the previous measurement by Borgeaud et al.[3],

$$k = 1200\ \mu\text{A/cm}^3/10^{13}\ \text{fluence}.$$

(2) Depletion Voltage: In a reverse bias rectifier, the thickness of charge depletion layer d is a function of concentration of donors N as $d = \sqrt{2\epsilon V_b/qN}$, where ϵ denotes the dielectric constant of material. A formation of defects in silicon crystal due to radiation increases concentration of donors N. Therfore it is expected that the bias voltage V_b must be increased to achieve the same depletion depth d.

Fig.5 shows voltage dependences of pulse height peak of penetrating β-rays for strips with various degrees of proton fluences[8]. As we expected, for the damaged samples, the bias voltages for full depletion is higher.

(3) Pulse Height Degradation: Pulse height distributions of penetrating β-rays are shown in Fig.6 for the severely radiated spot($3*10^{14}$ protons/cm^2). Clearly seen is a change in the width of the minimum ionizing peak and the pedestal. It is mostly due to the high leak current of 1.4 μA/strip. Fig.7 illustrates the dependence on the proton fluence. In this measurement, the bias voltage was adjusted to get full depletion. One sees there is no significant dependences, indicating no appreciable influences of radiation on carrier lifetime up to several Mega Rads.

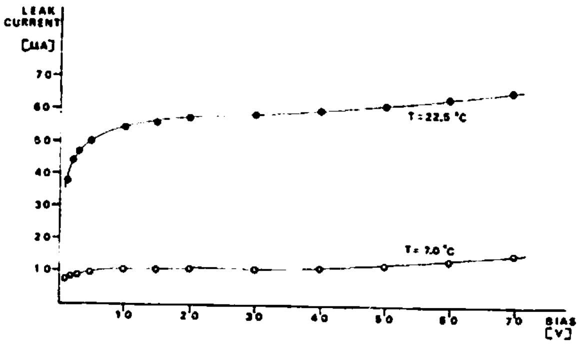

Fig.4 Total leakage current of the irradiated sample as a function of bias voltage V_b. Data were taken at 22.5°- and 7.0°C.

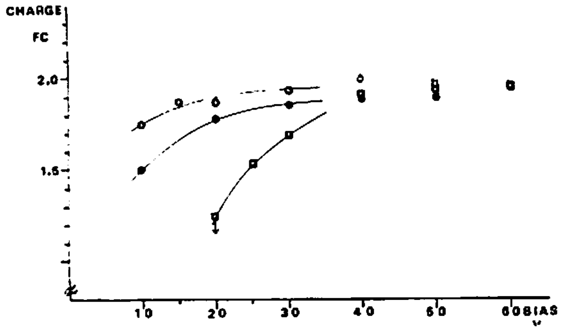

Fig.5 Bias voltage dependences of pulse height for penetrating β-rays at three severely irradiated spots. Local doses are ~1 MRAD (open circles), 3~4 MRAD (black circles) and 7~10 MRAD (open squares).

(4) Temperature Dependence: We discovered that the leak current caused by radiation damage is strongly sensitive to ambient temperature as is shown in Fig.8. This behaviour is quite normal as a semiconductor. As is clear by now, the limitation of silicon detectors comes not from physical damage or electrical breakdown, but from an increase of leak current which causes noise and eventually masks the peak of minimum ionizing particles as shown in Fig.6. Now, since we can reduce the leak current by a large factor just simply cooling detectors, there exists a possibility to make the silicon detector operational even after radiation much higher than 10^{14}/cm^2, probably up to 10^{15}/cm^2, equivalent to 30 Mega Rads. In fact, we have checked the pulse height distribution of penetrating β-rays at about 6°C as shown in Fig.9 for the same spot as for Fig.6. The clear separation between noise and signal has revived and, at the same time, FWHM of penetrating β-rays have recovered from ~65 % for Fig.6 to ~54 %. However the width seems to be slightly worse than for the non-damaged sample shown in Fig.1.

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References

1. G.Bellini et al., IEEE Nucl.Sci. NS-30(1983) 415.
2. B.Hyams et al., Nucl.Instr.Meth. 205(1983) 99.
3. P.Borgeaud et al., Nucl.Instr.Meth. 211(1983) 363.
4. E.H.M.Heijne, CERN Report 83-06 (1983).
5. The samples are provided by Hamamatsu Photonics Co., Hamamatsu, Japan.
6. Product of Nitto Electric Industrial Co.,Ltd.,Japan.
7. Fig.4 shows total leak current of 60 μA for summed up over all 56 strips, while Fig.3 indicates the strong bias voltage dependence as well as higher leak current of 20 μA for just three strips. This is because the leak current measurement for Fig.3 was done with side strips electrically floating.
8. The peak heights shown in Figs. 5,6,7 and 9 are systematically lower than the peak charges in Figs. 1 and 2. This is probably because they are different samples and there is a slight difference in thickness.

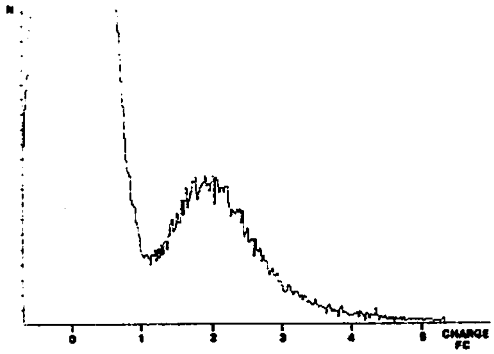

Fig.6 Pulse height distribution of penetrating β-rays at the spot of severely irradiated spot(7~10 MRAD) by 800 GeV protons. Data were taken at V_b=50 V, T=23.2°C and I_{leak}=1.4 μA/strip.

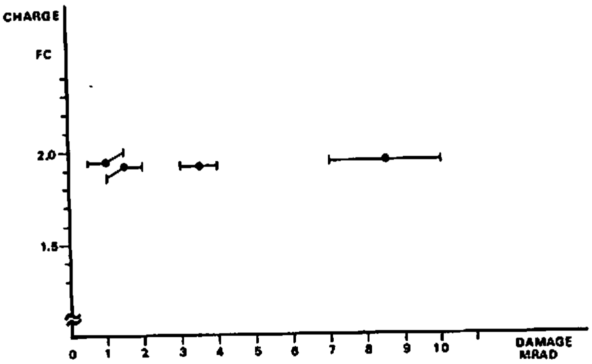

Fig.7 Penetrating β-ray pulse heights as a function of local radiation dose.

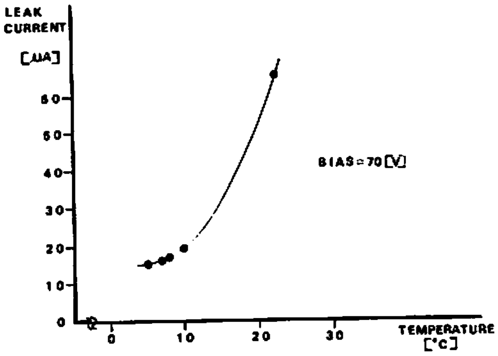

Fig.8 Temperature dependence of the total leakage current of irradiated sample.

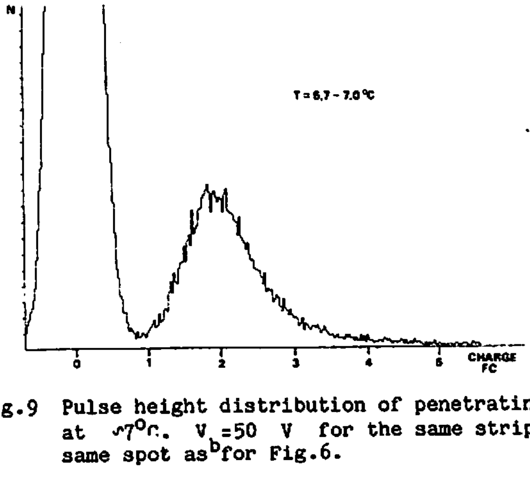

Fig.9 Pulse height distribution of penetrating β-rays at ~7°C. V_b=50 V for the same strip and the same spot as for Fig.6.