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First Observation of Thermal Runaway in the Radiation Damaged Silicon Detector

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Abstract

A silicon microstrip detector irradiated up to 4.2×10^{13} protons/cm² was demonstrated to give rise to detector thermal runaway. The temperature and voltage dependence can be fairly well reproduced by a finite element thermal simulation with temperature dependent bulk leakage current.

I. INTRODUCTION

Silicon microstrip detectors are expected to work in high radiation environments like LHC. Effects on radiation of the order of 10^{13-14} particles/cm²/year are mainly an increase of bulk leakage current [1], an increase of full depletion voltage, an effective inversion of bulk type from n to p, and a decrease of charge collection efficiency. It is important to keep the detector at or below 0°C in order to delay the anti-annealing effect. Thus it becomes important to consider a cooling scheme of detector system. Due to large leakage current, one cannot neglect the heat generation in the bulk any more. In addition, it is known that the bulk leakage current has a very strong positive dependence on temperature [2]. A. Seiden and W. Miller pointed out that detector thermal runaway may occur if heat is not removed effectively [3]. Although this prediction is a natural consequence of non-linear temperature dependence of leakage current, it must be demonstrated using

an actually radiation damaged silicon detector. Such a demonstration will be also useful to check any of thermal simulations handling thermal runaway phenomena.

We here report our demonstration for the first time that the thermal runaway in fact happens in highly radiated silicon detectors.

II. IRRADIATION

A SVX-2 layer-0 prototype sensor of 17×79 mm² with 0.3 mm in thickness for the CDF upgrade was irradiated with 12 GeV protons at the EP1-A beam line in the north experimental hall of KEK Proton Synchrotron in July 1995 [4]. Typical beam intensity was 2×10^{10} protons/pulse. The beam was 26 mm wide and 11 mm high in rms. The primary protons were radiated uniformly over the sensor using a remotely controlled x-y stage. The sensors were kept at 10°C in a cold box during irradiation of 1.5 hours. A bias voltage of 60 V was applied during the exposure. The accumulated fluence measured with an activation method using aluminum foils was 4.2×10^{13} /cm². The flux of thermal neutron in the beam area was also measured using gold foils covered with cadmium shields. The flux thus measured was 6×10^6 and 3×10^6 neutrons/cm²/s at 0.1m and 1m away from the beam line, respectively. Thus the effect of thermal neutron effect is considered to be small.

After the irradiation, the box was moved about 1 m from the beam line for 13 days before it was taken out from the area. The temperature of the samples were kept at 10°C Then the irradiated sensors were taken out of the area and stored in a refrigerator at near 0°C for 2 months.

III. SET UP OF THERMAL TEST

As shown in the Fig. 1, a cooling channel with water circulation was attached on one side of the sensor. A number of thermo-couples were mounted on various points for temperature measurement. A photograph of the set-up is shown in Fig. 2. As schematically shown in Fig. 3, the sensor thus equipped was enclosed in a vacuum tank of 25 cm in diameter in which the vacuum was kept at about 3 torr. The vacuum tank was placed in a temperature controlled box of 1m cube. A chilling unit controlled the temperature of

Fig. 1 Irradiated silicon microstrip sensor with cooling channels and thermo-couples attached.

circulating cooling water. The temperatures of the thermal box T_{env} and cooling water T_{cool} were continuously monitored to be stable within $\pm 0.1^\circ\text{C}$. The voltage was set externally by hand, while temperatures were printed with a multi-recorder. The total leakage current was monitored with a current meter.

Fig. 2. Photograph of the sensor part of the test setup.

Fig. 3. Setup of the test. The Si sensor is placed in a vacuum tank, which is kept in a large thermal box.

Fig. 4 illustrates a typical time profile on the recorder when a thermal runaway took place. It has happened in about ten minutes after the last voltage increment of 1 volt was applied. One sees that it takes a while before the temperature starts rising progressively as a function of time, as expected typically in this kind of runaway phenomena.

The point of thermal runaway critically depends on the temperature of the cooling water T_{cool} as well as that of the vacuum tank T_{env} . In the initial series of measurement, T_{env} was kept at 10°C higher than T_{cool} to make the radiation and/or convection effects small. Fig. 5 illustrates a typical V-I curve ($T_{cool}/T_{env} = 25 / 35^\circ\text{C}$). The voltage on silicon was stepped up by hand, coarsely at low voltage while finely near

Fig. 4. Time profile of thermal runaway recorder in a chart recorder after the voltage increment from 131 to 132 Volt in the case of $T_{cool} / T_{env} = 30 / 40^\circ\text{C}$.

Fig. 5. Voltage-current curve at $T_{cool} / T_{env} = 25 / 35^\circ\text{C}$.

the runaway point. At the point of runaway, the current limit of the power supply got active and the voltage was lowered automatically until it reached a stable point. In the same graph, typical values of temperature T_2 and T_5 as well as total power dissipation in the sensor are shown for several data points. The last point before runaway corresponds to 470 mW in this case.

Fig. 6 shows all of the V-T curves in which y axis is the temperature T_5 at the farthest point from the cooling side. It is clear that the higher the temperature of T_{cool} / T_{env} , the lower the runaway voltage is.

In the second test, the sensitivity on the temperature of the vacuum tank T_{env} was measured by changing T_{env} while the cooling temperature T_{cool} was kept the same. Fig. 7 indicates a fairly large dependence on T_{env} . This was not expected since the sensor was kept in a vacuum of 3 torr. Surface emission or absorption of infrared rays may play an important role.

Fig. 6. Voltage - T_5 (temperature of the farthest point) curve. The dotted lines are ANSYS simulation.

Fig. 7. Dependence on T_{env} at $T_{cool} = 30^\circ\text{C}$. The dotted lines are ANSYS simulation.

IV. THERMAL SIMULATION

We have simulated the observed thermal runaway with ANSYS V.5.1. A 2-dimensional element with temperature dependent heat generation is used [5]. The dependence of the bulk leakage current assumed is [6]

$$i_{leak} = i_0 \left(\frac{T}{T_0} \right)^2 \exp \left[- \frac{1.23 \text{ eV}}{2k_B} \left(\frac{1}{T} - \frac{1}{T_0} \right) \right]$$

where $T_0 = 273\text{K}$, k_B is the Boltzmann constant and i_0 is the leakage current at 0°C . It should be noted here that we assume no voltage dependence of i_{leak} . There are three free parameters in the system:

- k_{cool} : thermal conductivity to the cooling channel,
- h_{conv} : film coefficient for surface emission,
- i_0 : leakage current at 0°C

For the time being the convection formalism in ANSYS program is used for thermal emission and/or absorption from/to the silicon surface. First two parameters were adjusted to reproduce the temperature profiles along the sensor of the cases of $T_{cool}/T_{env} = 30/30$, $30/40$ and $30/50^\circ\text{C}$ with no voltage on silicon. The simulation well reproduces all the cases with an effective value of $h_{conv} = 4.2 \text{ W/m}^2\text{K}$.

The leakage current constant i_0 is then obtained by adjusting it to reproduce one of the thermal runaway point at 130V for $T_{cool}/T_{env} = 30/40^\circ\text{C}$. The value $i_0 = 0.044 \mu\text{A/mm}^2$ thus obtained corresponds to the room-temperature (20°C) damage constant of $2.5 \times 10^{-17} \text{ A/cm}$. Once these parameters are fixed, ANSYS simulation can be done for various cases. The simulation results are overlayed in Figs. 6 and 7. One sees the simulation reproduces the experimental data fairly good though not exact. In the case of Fig. 7, i_0 for simulation had to be reduced to $0.041 \mu\text{A/mm}^2$, which is an indication of heat annealing during the present test.

V. SUMMARY

We have observed detector thermal runaway in the irradiated silicon detector for the first time. The runaway point critically depends on the cooling temperature as well as the environmental temperature. Even in the vacuum of 3 torr, there exists a large dependence of ambient temperature, suggesting thermal emission/absorption from surface is significant. ANSYS thermal simulation with temperature dependent leakage current reproduces the runaway points fairly well. The damage constant obtained as one of parameters is $2.5 \times 10^{-17} \text{ A/cm}$.

In conclusion, the thermal runaway in fact occurs in radiation damaged detectors as predicted.

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