Evolution of silicon micro-strip detector currents during proton irradiation at the CERN PS

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Abstract

The current evolution of full-sized prototype silicon micro-strip detectors for the ATLAS SCT during proton irradiation with the 24 GeV beam from the CERN PS is described. It is shown that the measured detector currents agree well with the predictions of bulk radiation damage parameterizations, indicating that the detector design is robust against other damage effects.

Introduction

The silicon micro-strip detectors in the ATLAS Semiconductor Tracker (SCT) will be subject to unprecedented levels of radiation; simulations have predicted that the inner layers of the SCT will receive approximately 1.4×10^{14} 1 MeV equivalent neutrons per cm^2 in the 10 year lifetime of the experiment [1]. The majority of this radiation is due to charged hadrons from the primary interaction and neutrons backscattering from shower cascades in the calorimeters [2], therefore detectors should be irradiated with charged hadrons, to address both ionisation and displacement damage. The 24 GeV primary proton beam from the CERN Proton Synchrotron is used as it enables the target fluence to be reached within a reasonable time-scale.

During irradiation the detector currents are monitored and recorded automatically, and this has provided an opportunity to study the evolution of detector currents during proton irradiation, in a thermal environment similar to that of the ATLAS detector. Comparisons can then be made with the predictions of bulk radiation damage parameterizations derived from post irradiation studies of silicon diodes [3], and the values for the constants of these parameterizations calculated specifically for ATLAS micro-strip detectors.

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The Irradiation Facility

To enable a large number of detectors to be irradiated efficiently a dedicated irradiation facility has been established in the East Experimental Hall of the CERN Proton Synchrotron. A primary beam is used to irradiate the detectors with 24 GeV protons, which are incident on the detectors in approximately 0.5 second spills, each containing between 20 and 40×10^{10} protons, with 1 to 3 spills being received per 14 second PS super-cycle. The target fluence for proton irradiation is 3×10^{14} pcm⁻², which is derived from the predicted 1 MeV equivalent neutron fluence using a proton hardness factor of 0.68 and a 50% over estimation. Recent results [4] indicate that the proton hardness factor may actually be 0.51, but for consistency across the irradiations the target fluence of 3×10^{14} pcm⁻² has been retained. This fluence can be achieved in between 6 to 14 days depending on beam conditions.

During irradiation the detectors are kept in a constant environment and cooled to approximately the ATLAS SCT design operating temperature [1]. This is achieved by containing the detectors in a thermally insulated Styrofoam enclosure cooled by the passage of an antifreeze-water mixture through heat exchangers. An even temperature and a dry atmosphere are maintained through the use of flat pack blower fans and a constant flow of dry nitrogen. Temperatures within the enclosure are monitored using pt100 thermistors, and are seen to be stable to within $\pm 0.2^\circ\text{C}$.

To ensure that the detectors receive a uniform irradiation the insulated enclosure is mounted on an x-y stage and constantly scanned through the beam-line. In this way full-size 6.3×6.4 cm detectors can be fully irradiated with the approximately 1×2 cm proton beam.

Throughout the irradiation the detectors are biased in order to provide an electric field across the oxide layer with the strips grounded to allow the oxide to discharge. Each detector is biased independently and individual detector currents are monitored automatically and fed into an alarm system that signals detector breakdown.

Bulk Radiation Damage Parameterizations

Irradiation of silicon causes two types of damage; bulk damage and surface damage. Bulk damage has two effects on the detector. Firstly, the effective carrier density is altered by the removal of donor atoms and the creation of acceptor atoms, causing the detector to go through type-inversion. This process has been parameterized as [5]

$$N_{eff}(\phi) = N_{eff}(0)e^{-c\phi} - \beta\phi \quad (1)$$

where $N_{eff}(\phi)$ is the effective carrier density after fluence ϕ , $N_{eff}(0)$ is the initial effective carrier density, c is the rate of donor removal and β is the rate of acceptor creation. No annealing terms have been included as their contribution is expected to be negligible for the temperatures and time-scales considered here [6]. The form of this parameterization can be seen in Figure 1.

Secondly, the leakage current increases, due to the creation of deep traps which encourage the formation of electron-hole pairs. This process has been parameterized as [7]

$$\Delta I = \alpha\phi.\text{Vol} \quad (2)$$

where ΔI is the change in bulk detector leakage current, α is the damage constant, ϕ is

Figure 1: Parameterization of the change in effective carrier density

the fluence and Vol is the active volume of the detector.

To obtain the current predicted from bulk effects it is necessary to combine these two parameterizations, and this can be done by considering low fluence and high fluence regions separately.

Before irradiation, the full depletion voltage for a $300\text{ }\mu\text{m}$ thick detector is typically about 80V. Throughout the irradiation the detectors are biased at 100V, and are thus fully depleted when irradiation begins. The donor removal term in equation (1) initially causes the effective carrier density to decrease (see figure 1), and since

$$V_{dep} = \frac{e|N_{eff}|d^2}{2\epsilon} \quad (3)$$

(where V_{dep} is the full depletion voltage, e is the electron charge, d is the detector thickness and ϵ is the dielectric constant of silicon) the full depletion voltage will decrease also. So the detector will remain fully depleted, and the active width of the detector will be constant (the full width of the detector). Therefore from equation (2), and assuming the initial detector current to be negligible i.e. $I_{meas} \approx \Delta I$ (initial currents of approximately 500 nA are observed), a linear relationship between detector current and fluence should be observed at low fluences, $I_{low} \propto \phi$.

At high fluences the donor removal term in equation (1) becomes negligible so

$$|N_{eff}(\phi)| \approx \beta\phi$$

This causes the full depletion voltage to increase (see figure 1 and equation (3)) so for a fixed bias voltage the detector is no longer fully depleted. The width of the depleted region w can be calculated using

$$\begin{aligned}
w &= \sqrt{\frac{2\epsilon}{e} \frac{V_{bias}}{|N_{eff}|}} \\
&\approx \sqrt{\frac{2\epsilon}{e} \frac{V_{bias}}{\beta\phi}}
\end{aligned} \tag{4}$$

where V_{bias} is the bias voltage applied to the detector. By substituting $\text{Vol} = Aw$, where A is the detector area, into equation (2) then

$$\begin{aligned}
I_{meas} &\approx \alpha\phi A \sqrt{\frac{2\epsilon}{e} \frac{V_{bias}}{\beta\phi}} \\
&\approx \alpha A \sqrt{\frac{2\epsilon}{e} \frac{V_{bias}}{\beta}} \phi^{0.5}
\end{aligned} \tag{5}$$

So, at high fluences the detector current should be proportional to the square root of the fluence, $I_{high} \propto \phi^{0.5}$

Measured Detector Currents During Irradiation

The automated current monitoring system of the irradiation facility measures and records the detector current every 1 to 2 minutes throughout the irradiation. The received fluence is measured using a secondary emission counter in the beam line that is calibrated by the activation of aluminium foils [8]; an accuracy on the measured fluence of better than 10% is obtained.

Thirteen full size 6.3×6.4 cm $300 \mu\text{m}$ thick p-in-n detectors with 770 AC coupled strips, from 3 different manufacturers, were irradiated to the target fluence of $3 \times 10^{14} \text{ pcm}^{-2}$ whilst reverse-biased at 100V. The irradiation took 5.9 days and was carried out at a temperature of $-9.4 \pm 0.2^\circ\text{C}$. A subset of a typical current-fluence profile is shown in Figure 2.

The difference between the low and high fluence regions is clearly shown. By fitting a straight line to a plot of $\log I$ vs. $\log \phi$ it is possible to obtain the relationship between current and fluence for both the low ($\phi < 3 \times 10^{13} \text{ pcm}^{-2}$) and high ($\phi > 2 \times 10^{14} \text{ pcm}^{-2}$) fluence regions. These are given in table 1. The average values found (with statistical errors) are:

$$\begin{aligned}
I_{low} &\propto \phi^{0.98 \pm 0.02} \\
I_{high} &\propto \phi^{0.52 \pm 0.01}
\end{aligned}$$

These agree with the behaviour expected from the above discussion.

Modelling Detector Currents

To formulate a complete model of how detector currents evolve with fluence it is now necessary to derive the values of α , the damage constant, and β , the rate of acceptor creation.

Figure 2: Current vs. fluence for detector biased at 100V

From equation (2) α can be found from a linear fit to a plot of I vs. ϕ for low fluence data and from equation (5) β can be found from a linear fit to a plot of I^2 vs. ϕ for high fluence data. The results of deriving these parameters for all 13 detectors are shown in Table 1. The average values (with statistical errors) are

$$\begin{aligned}\alpha &= (2.93 \pm 0.04) \times 10^{-18} \text{ Acm}^{-1} \\ \beta &= 0.0452 \pm 0.0016 \text{ cm}^{-1}\end{aligned}$$

Figure 3 shows the predicted current from the bulk radiation damage parameterizations using these values, along with current data from 6 of the 13 detectors irradiated.

Discussion

As can be seen in Table 1, almost all of the irradiated detectors agree with the $I \propto \phi$ relationship at low fluences and the $I \propto \phi^{0.5}$ relationship at high fluences predicted by the bulk radiation damage parameterizations (equations (1) and (2)). There is only one detector (number 7) that deviates significantly from this, but the mean of all detectors is in good agreement.

The damage constant α at $-9.4 \pm 0.2^\circ\text{C}$ was found to be

$$\alpha(-9.4 \pm 0.2^\circ\text{C}) = (2.93 \pm 0.04) \times 10^{-18} \text{ Acm}^{-1}$$

and normalizing to a temperature of 20°C [9] gives

$$\alpha(20^\circ\text{C}) = (5.67 \pm 0.09) \times 10^{-17} \text{ Acm}^{-1}$$

Figure 3: Bulk radiation damage model with constants derived from irradiated detectors, compared to data from detectors 1,2,3,4,5 and 7.

This value is comparable with those found by other groups for proton irradiation at the CERN PS, for example $\alpha(20^\circ\text{C}) = 5.0 \times 10^{-17} \text{ Acm}^{-1}$ [9] and $\alpha(20^\circ\text{C}) = 5.4 \times 10^{-17} \text{ Acm}^{-1}$ [10].

The rate of acceptor creation β was found to be

$$\beta = 0.0452 \pm 0.0016 \text{ cm}^{-1}$$

This value is considerably larger than has been previously obtained by other groups, for example $\beta = 0.011 \text{ cm}^{-1}$ [9, 10], $\beta = 0.0108 \text{ cm}^{-1}$ [5] and $\beta = 0.016 \text{ cm}^{-1}$ [7]. However, it is difficult to make direct comparisons due to differences in the measurement processes. These values are based on data taken after post-irradiation annealing, whereas the value obtained here is based on data taken during irradiation.

Figure 3 shows that there is a good agreement between the measured data and the model derived from bulk radiation damage parameterizations. This implies that damage to the bulk is the only significant damage effect, and that the detector design is robust against other forms of radiation damage.

Summary and Conclusions

Prototype full-size ATLAS silicon micro-strip detectors have been irradiated to the predicted 10 year dose using a beam of 24 GeV protons in a dedicated detector irradiation facility at the CERN PS. The detector currents have been monitored throughout the irradiation. It has been shown that the measured detector currents agree well with the predictions of bulk radiation damage parameterizations, and values for the damage constant α

and the rate of acceptor creation β have been derived. The good agreement between measured detector currents and those predicted by bulk radiation damage parameterizations implies that the detector design is robust against surface damage effects.

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Appendix

Detector	a	b	$\alpha(\times 10^{-18} \text{Acm}^{-1})$	$\beta(\text{cm}^{-1})$
1	0.989 ± 0.007	0.568 ± 0.002	2.98 ± 0.02	0.0427 ± 0.0003
2	0.987 ± 0.008	0.474 ± 0.003	2.82 ± 0.02	0.0479 ± 0.0004
3	0.979 ± 0.006	0.501 ± 0.002	2.92 ± 0.02	0.0442 ± 0.0004
4	1.015 ± 0.006	0.563 ± 0.001	2.94 ± 0.02	0.0411 ± 0.0003
5	1.008 ± 0.008	0.477 ± 0.003	2.82 ± 0.02	0.0481 ± 0.0004
6	0.986 ± 0.006	0.469 ± 0.002	3.25 ± 0.02	0.0576 ± 0.0004
7	0.795 ± 0.010	0.510 ± 0.002	2.58 ± 0.03	0.0355 ± 0.0004
8	0.909 ± 0.010	0.519 ± 0.002	3.10 ± 0.03	0.0532 ± 0.0005
9	0.966 ± 0.005	0.490 ± 0.002	2.91 ± 0.02	0.0447 ± 0.0004
10	1.012 ± 0.018	0.501 ± 0.002	2.91 ± 0.02	0.0452 ± 0.0003
11	1.013 ± 0.009	0.561 ± 0.002	2.93 ± 0.02	0.0436 ± 0.0003
12	1.038 ± 0.029	0.568 ± 0.002	2.90 ± 0.02	0.0409 ± 0.0003
13	0.974 ± 0.006	0.572 ± 0.002	2.99 ± 0.02	0.0423 ± 0.0003

Table 1: Table showing the results of linear fits to a log-log plot of low fluence data ($\phi < 3 \times 10^{13}$) where $I \propto \phi^a$, high fluence data ($\phi > 2 \times 10^{14}$) where $I \propto \phi^b$, and the derived constants α and β .