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Radiation Damage Studies for the DØ Silicon Detector [⋆]

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Abstract

We report on irradiation studies performed on spare production silicon detector modules for the current DØ silicon detector. The lifetime expectations due to radiation damage effects of the existing silicon detector are reviewed. A new upgrade project was started with the goal of a complete replacement of the existing silicon detector. In that context, several investigations on the radiation hardness of new prototype silicon microstrip detectors were carried out. The irradiation on different detector types was performed with 10 MeV protons up to fluences of 10^{14} p/cm^2 at the J.R. Mcdonald Laboratory at Kansas State University. The flux calibration was carefully checked using different normalisation techniques. As a result, we observe roughly 40-50% less radiation damage in silicon for 10 MeV p exposure than it is expected by the predicted NIEL scaling.

Key words: silicon detector, Tevatron, vertex detector, radiation damage
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1 Introduction

In April 2001 Fermilab's $p\bar{p}$ collider Tevatron started its Run II operation with the initial goal of reaching a twenty-fold increase in luminosity in the first running phase compared to the previous Run I. Both experiments at Tevatron,

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[⋆] Talk given by Frank Lehner at the 6th International Conference on Large Scale Applications and Radiation Hardness of Semiconductor Detectors, RD'03 (Florence, Italy, September 29 - October 1, 2003).

[1] http://www-d0.fnal.gov

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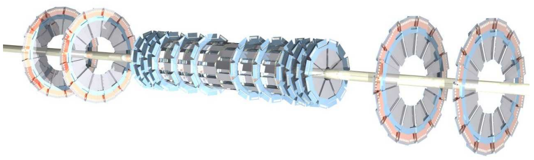

Fig. 1. The layout of the DØ silicon detector with its barrel/disk geometry.

DØ and CDF had installed major upgrades in their detectors. Among those upgrades, the new silicon vertex detectors which were commissioned in 2001 represent the center pieces of the experiments in order to achieve the ambitious physics goals of Run II.

The DØ silicon detector was designed [1] to provide both tracking and vertexing information over a $|\eta|$ coverage of up to 2.5. The layout of the detector and its service/supply lines was mainly driven by the relative large interaction region at Tevatron of $\sigma_z \sim 25$ cm. The silicon detector consists of 6 barrels in four layers with interspersed disks, with barrel modules primarily measuring the r-ϕ coordinate and the disk detectors which measure the r-z as well as r-ϕ. The layout of the DØ barrel/disk geometry is shown in figure 1. The detector was designed and its components tested, for an expected life time assuming a delivered luminosity at Tevatron of 2 fb^{-1}, corresponding to a fluence of about $1.3 \cdot 10^{13}$ 1 MeV n/cm^2 in the innermost layer. The concept of having a minimal mass within the detector led to the decision of using mostly double-sided silicon microstrip sensors. Due to the complex barrel/disk geometry a variety of different detector geometries and technologies as well as different sensor vendors were used.

2 The Lifetime of the Run IIa DØ Silicon Detector

We have carried out an irradiation study aiming for predicting the lifetime of the silicon detector. In this investigation we used Run II spare production silicon ladders that were identical to the ones installed in the experiment. The irradiation was performed in five steps at the proton Booster facility at Fermilab up to a total fluence of $3.7{\cdot}10^{13}$ 1 MeV n/cm^2, almost a factor 3 higher than the expected dose of Run IIa. Figure 2 shows the measured depletion voltage as a function of the fluence for several detector types. A near infrared laser was used to generate signals in the silicon detectors. The induced charge on the readout strips in the illuminated area was measured as a function of the applied bias voltage. In the resulting detector response curves, the depletion voltage was then defined as the intersection of two straight lines fitted to the linear region and to the plateau region respectively. The attributed relative uncertainty in this depletion voltage determination method was estimated to be at most 10% for unirradiated detectors increasing rapidly to about 20-25%

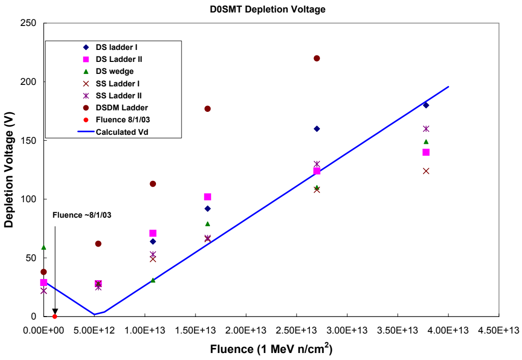

Fig. 2. The measured depletion voltage as a function of 1 MeV equivalent neutron fluence. The depletion voltage of the DSDM detector could not be reliably determined at the highest fluence point. The arrow in the graph indicates the actual accumulated fluence of the DØ silicon detector as of August 2003.

after irradiation mainly due to largely increased currents.

The continuous line in the graph represents a parameterisation based on the so-called Hamburg model [2], which includes radiation induced stable damage as well as annealing and reverse annealing effects. While the model prediction gives for most of the measured detector types a fair description, the double sided double metal (DSDM) sensors exhibit a rise that is more than a factor two faster than other devices. This is a major concern for the b-tag efficiency, since these devices are used in the innermost layer of the central barrels. A separate irradiation test [3] performed on single planar test diodes which were part of the DSDM wafers showed depletion characteristics similar to the other detector types, indicating that the additional PECVD[2] layer in between the two metal layers or the double metal processing itself causes increased sensitivity to radiation.

The operational limit on our double sided detectors is given by unacceptable large bias voltages across the coupling capacitors necessary to deplete the detectors. Shorted capacitors cause the input of our front end chip to saturate and to drive currents into the substrate affecting the pedestals of several neighbour channels. Therefore, we split the bias between the two detector sides to minimise the maximum potential on the coupling capacitors and hence reducing the breakdown risk. Although the breakthrough voltage of the coupling capacitors was specified at about 150 V and on the detector channels tested up to 100 V, it might be lowered due to aging effects and mechanical stress during bonding, so that our biasing is limited to probably 100-120 V per side

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[2] plasma enhanced chemical vapour deposition

only.

In addition there is another serious limitation on many of our double-sided devices. The p-side bias on unirradiated sensors has to be limited to only a few volts, otherwise breakdown effects due to micro-discharge occur. This micro-discharge breakdown is caused by increased electric fields in the vicinity of external AC coupling structures which are kept at the ground potential of the preamplifier. Misalignment of the metal layers or residual charge in the oxide can lead to even lower breakdown thresholds. Before irradiation, the p-side is mostly affected due to the pn-junction being on that side. After irradiation and type inversion however, the junction moves to the n-side and becomes more susceptible to micro-discharge. Indeed, we have observed such an increased noise on the n-side of our double-sided devices during our irradiation studies, that exhibits characteristics typical of micro-discharge. This rapid noise increase requires us to define the lifetime limitation of the inner layer of DØ silicon detector as the onset of micro-discharge effects. From our Booster data we expect that the n-side noise will become unacceptable for total bias voltages between 130 and 170 V, while the p-side noise might be tolerable up to 200 V. Our best estimate is therefore, that we will lose precision r-z measurements from the n-side of the DSDM detectors between 1 - 2 fb^{-1} and the inner layer will be unusable at a total bias exceeding 200 V or about 3.5 fb^{-1}.

3 Radiation Studies for Run IIb

The extended running period of the Tevatron accelerator up to the year 2009 makes an upgrade of the existing DØ silicon detector mandatory[3]. A new improved detector design was worked out employing 6 layers of single sided sensors. Since the inner layers of this upgrade will be now closer to the beam pipe the new sensors have to be radiation hard up to 10^{14} 1 MeV n/cm^2.

New prototype single sided sensors manufactured on standard n-type FZ silicon were ordered from Hamamatsu and have been extensively characterised in 2002/2003 in order to qualify them for the upgrade project. The 320 μm thick sensors have a single guard ring with a peripheral n-well structure. The sensor pitch is 25 μm with every second strip AC coupled. The electrical properties of the received sensors were excellent. They could be biased up to 800 V without any major sign of a junction breakdown. A subset of the sensors was irradiated with low energy protons in order to test the radiation hardness.

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[3] However, the director of Fermilab, Michael Witherell, announced on Sept 3, 2003, that "we will not include the silicon detectors (CDF & DØ) in the continuing upgrade project“

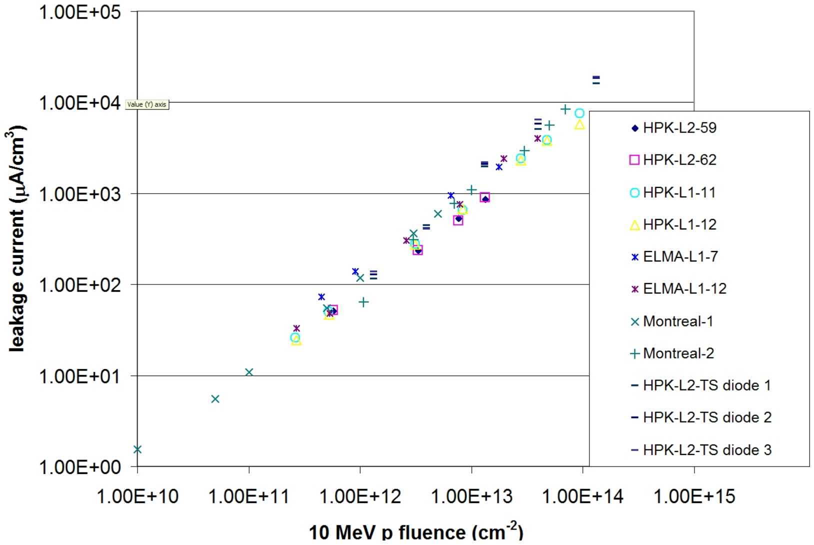

Fig. 3. The measured leakage current at 20°C normalised to the sensor volume as function of the 10 MeV proton fluence. The data from reference [4] are labelled as Montreal.

We have used the 7 MV Tandem van de Graaf accelerator lab located at the Kansas State University (KSU) James R. Macdonald Laboratory[4]. The beam energy was set to 10 MeV protons and the beam size at the target was approximately 3 mm in diameter. The silicon detectors were mounted on aluminium frames in an evacuated target chamber. The beam was rastered independently over the samples in the x and y planes using an electrostatic deflector in order to achieve uniform irradiation.

We have performed the irradiation in various steps up to a total accumulated dose of $1.2 \cdot 10^{14}$ p/cm^2. Immediately, after each irradiation step the sensors were annealed at 60°C for 80 minutes. The radiation exposure was monitored by a beam current monitor and more accurately with a current integrating Faraday cup which was placed directly behind the sensors. Several checks were performed to verify the integrated flux measurements of the Faraday cup. A careful analysis of activated 1.5 mil thick copper foils agreed with the result from the direct fluence measurements on a 10% level.

In figure 3 the leakage current data is presented as a function of 10 MeV proton fluence. Results from a similar irradiation study [4] by the RD48 collaboration are shown for comparison. Generally, there is a good agreement between the data sets. The linearity of the leakage current rise persists to proton fluences above 10^{14} cm^{-2}. The measured radiation damage is also consistent among the three silicon sensor types and test diodes which we used in the irradiation.

Based on a linear fit of the form $I = I_0 + \alpha_p \cdot \Phi$ with Φ being the 10 MeV pro-

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[4] http://www.phys.ksu.esu/area/jrm/

ton fluence and α_p the so-called current related damage constant for 10 MeV protons, we obtain $\alpha_p = 11.6 \cdot 10^{-17}$ A/cm. This leads then to a hardness factor k of the proton beam of $k = \alpha_p/\alpha_n(1 \text{ MeV n})$[5] =2.5. This observed value has to be compared to the theoretical hardness factor calculated under the assumption of the NIEL hypothesis [5]. Taking the energy loss of 10 MeV protons in 320 μm thick silicon of approximately 3 MeV into account, the theoretical hardness factor can be calculated to be 4.5. Hence, our observed bulk radiation damage is about 40-50% lower than the anticipated NIEL damage. A similar conclusion was reached by the RD48 Collaboration [4] in their irradiation test and now independently verified.

4 Summary

An irradiation study on spare production ladders of the DØ silicon detector was performed at the 8 GeV proton Booster at Fermilab. The depletion voltage measurements revealed that a particular detector type exhibited increased sensitivity to radiation, which is likely caused by the additional PECVD insulation in between the double metal layers. Increased noise caused by microdischarge effects has been observed and will introduce an upper limit on the total operating bias voltage. According to our best estimates, we believe that the useful life time of the DØ silicon detector will be limited to around 3.5 fb^{-1}.

New prototype silicon sensors that were ordered for the new silicon upgrade project have been irradiated. The results based on the obtained sensor leakage currents after irradiation show a 40-50% deviation from the NIEL scaling hypothesis for low energy protons. This is in agreement with other observations made by the RD48 collaboration.

References

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[2] M. Moll, Radiation Damage in Silicon Particle Detectors - Microscopic Defects and Macroscopic Properties, DESY-Thesis-1999-040

[3] S. Lager, Proton-Induced Radiation Damage in Double-Sided Silicon Diodes, Master's Thesis, Stockholm University 2002

[4] D. Bechevet et al., Nucl. Instr. Meth. **A479:487-497**, 2002

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[5] We use here the RD48 adopted value for α_n=4.56$\cdot 10^{-17}$A/cm

[5] G.P. Summers et al., IEEE NS40 (1993)1372