Depletion Voltage and Charge Collection for Highly Irradiated Silicon Microstrip Detectors with Various Initial Resistivities*

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Abstract

We have irradiated p-on-n silicon microstrip detectors of initial bulk resistivity between 0.2 and 2.7 k Ω -cm with 55MeV protons to fluences of 0.8, 2.2 and 11x10¹³ p/cm² (equivalent to twice the fluence in high energy protons), and have measured the depletion voltage before and after irradiation using C-V methods.

In addition, we have measured the charge collection of minimum ionization on a single strip with a fast amplifier as a function of bias voltage. We compare the depletion voltage deduced from both methods for samples with different initial resistivities.

I. INTRODUCTION

In future high-energy experiments, silicon strip and pixel detectors will be increasingly used in high radiation environment. For example at the LHC, the fluence over the lifetime of detectors will reach 2x10¹⁴ p/cm² for strips and about 1x10¹⁵ p/cm² for pixels. While the increase in leakage current due to radiation will be controlled by cooling and, in the case of pixels, reduced sensitive volume, one still has to face the radiation-induced change in effective doping concentration (N_{eff}). This change in N_{eff} makes the detector effectively more “p”-type, leading to type inversion of an initial n-bulk to a p-bulk, which ultimately leads to very high depletion voltages [1].

There is evidence that using low-resistivity n-bulk material for detector fabrication will reduce the final depletion voltage after large fluences[2,3]. This evidence is mostly from a) static C-V measurements where the depletion voltage is determined from the fact that, after depletion, the body capacitance is independent of the bias voltage; and b) test pad detectors made specifically for general study on radiation damage problem. In particle detector application, where the charge collection on strips or pixels is important, the depletion voltage is the bias voltage at which the collected charge reaches a plateau. In this experiment, we determined the depletion voltage using both methods for p-on-n silicon strip detectors with different initial resistivity.

II. DEPLETION VOLTAGE FROM CAPACITANCES

(C-V), PRE-RAD

A. Detectors

Silicon microstrip detectors with p-implant of 100micron pitch in n-bulk of different doping density and thickness were prepared in the BNL detector laboratory. The number of detectors, their resistivity and thickness are summarized in Table 1. In addition, the fluence of 55MeV protons received by the detectors is shown, which should be multiplied by approximately a factor 2 to get the corresponding high energy (HE) proton fluence.

B. Capacitance as a Function of Bias

While the depletion voltage of detectors with higher resistivity ($\geq 1.2\text{k}\Omega\text{-cm}$) could be determined directly from C-V curves, the one for lower resistivity were inferred from plots of $1/C^2$ vs. bias as follows. Using the plate capacitor equation relating the capacitance C, the area A and the thickness t:

$$C = \epsilon * \epsilon_0 * A / t, \quad (1)$$

and the equation relating the bias voltage V, the doping density N (inversely proportional to the resistivity) and the thickness of the depleted region t

$$V = qN / (2 * \epsilon * \epsilon_0) * t^2 \quad (2)$$

we can express $1/C^2$ as a function of V and N:

$$1/C^2 = (2 / q * \epsilon * \epsilon_0 * A^2) * (1/N) * V, \quad V < V_{dep} \quad (3)$$

If the bias equals or exceeds the depletion voltage, the capacitance is constant:

$$1/C^2 = \text{const} = 1 / C_{min}^2, \quad V \geq V_{dep} \quad (4)$$

Thus the depletion voltage is given by the intersect of the straight line with linear voltage dependence below depletion and the saturated, constant line above depletion.

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Table 1 Depletion Voltage of the Detectors

	Detector #					
	A1	A2	A4	A3	A1	
Resistivity [kOhm-cm]	0.43	0.43	0.22	1.3	1.3	2.7
Proton Fluence 55MeV [10 ¹³ /cm ²]	0	2.2	11	2.2	11	0.8
Thickness d [μ]	390	390	390	295	295	280
Min.Cap Pre-rad [pF]	49	49	49	64	60	61
Dep. Volt. C-V Pre-rad	1100 *	1100 *	2160 *	203	208	100
Dep. Volt. C-V Pre-rad , 300μ	650 *	650 *	1280 *	210	215	115
Dep.Volt C-C Pre-rad	1100 *			210		
Dep.Volt C-C Pre-rad, 300μ	650 *			217		
Dep. Volt. C-V Post-rad		790- 890	360- 430	85- 110	200 220	47- 53
Dep. Volt. C-V Post-rad , 300μ		470- 530	210- 260	89- 114	207 227	54- 60
Dep.Volt C-C Post-rad						
Dep. Volt. C-C Post-rad , 300μ						
Inverted?	n.a.	No* C-V	No C-V	Yes C-V	No C-V	No C-V

* extrapolated

C. Determination of Resistivity and Depletion Voltage

Fig. 1 shows the determination of the depletion voltage for 4 detectors. The parameter $1/C^2$ is plotted as a function of the bias voltage. The detector with resistivity 1.3 Ohm-cm shows the saturation of the capacitance at about 200V, and we will discuss it further below. Lower resistivity detectors have a resistivity of 430 and 220 Ohm-cm as determined from the slope of the curves. Given their thickness of 390μm, their saturated capacitance is expected to be $C_{min} = 49\text{pF}$. This yields depletion voltages of 1100V and 2160V, respectively.

In the following, we will, for comparison, refer all depletion voltages to a common thickness of 300 μm, which means dividing the measured depletion voltages by a factor $(d/300)^2$, where d is the thickness of the detector in μm.

Fig. 1 Pre-rad plot of $1/C^2$ vs. bias voltage for several of the detectors

III. DEPLETION VOLTAGE FROM CAPACITANCES (C-V), POST-RAD

A. Frequency Dependence in the post-rad C-V curves

The depletion voltage was determined for all detectors pre-rad and post-rad using the C-V method. The capacitance was measured as a function of the bias voltage for a range of frequencies from 500Hz to 1MHz using the HP 4281 LCR meter. As outlined above, the quantity $1/C^2$ was plotted as a function of the bias and the depletion voltage determined as the intercept of the slope with a constant line corresponding to a constant capacitance. This is shown for an irradiated detector in Fig. 2.

Fig. 2 Plot of $1/C^2$ vs. bias voltage for an irradiated detector

As evident in Figure 2, the C-V curves have strong frequency dependence in irradiated detectors, and depending on the frequency chosen, the depletion voltage extracted will

vary widely. Previously [4], the best method used the low-bias data at 10kHz to establish the slope and intercept it with the pre-rad minimum capacitance $C_{\min}$ (60fC in Fig. 2). A measure of the systematic uncertainty of this method is given by the intercept of the slope with a horizontal line which passes through the highest points in the 10kHz curve as shown in Figure 2 and thus represents the minimum post-rad capacitance. The range of depletion voltages thus derived from Fig. 2 is 180-210V.

B. Depletion Voltage for different resistivities

Figure 3 shows the depletion voltage of all detectors as a function of high-energy proton fluence, where the depletion voltage is normalized to a 300 μ m detector thickness. The points are taken after annealing of at least 100 hrs at room temperature (RT) - see below. The two points shown for the same fluence show the uncertainty in the determination of the depletion voltage for the frequency of 10kHz. Data for the highest neutron fluence of $2.2 \cdot 10^{14}$ are available for two resistivities: 220Ohm-cm and 1.3kOhm-cm. While the initial depletion voltages differ by a factor 6, the final depletion voltages end up close to 210V, although one is inverted.

Fig. 3 Depletion voltage as a function of fluence for detectors with different resistivity, scaled to 300 μ m thickness.

Figure 3 shows straight lines motivated by the findings of the Rose Collaboration [2,3], that the inversion fluence F_{inv} , i.e. the point where the depletion voltage is zero when the bulk inverts from n-type to p-type depends linearly on the initial doping density N_{init} [3]. We find as an approximate relationship:

$$F_{\text{inv}} = 13 \cdot N_{\text{init}} \quad (5)$$

C. Determination of Inversion

In order to apply eq. 5 one has to know if the detectors are inverted or not. This can be decided with different methods: here we are using both the room temperature annealing behavior of the depletion voltage from C-V measurements [5]. The annealing consists of a short term

annealing with an characteristic time of days at room temperature (RT), followed by a long term annealing in the opposite direction, which lasts about 200 times longer. For non-inverted detectors, the initial doping concentration dominates the N_{eff} , leading to a shallow maximum in the depletion voltage. Inverted detector will show a pronounced minimum after a few days. The RT annealing curves are shown in Fig. 4 for all five irradiated detectors: only the detector with resistivity of 1.3k Ohm-cm is clearly inverted at the highest fluence.

Fig. 4 Depletion voltage as a function of RT annealing time for all five detectors, scaled to 300 μ m thickness.

The lines in Fig. 3 take into account the annealing behavior, and the conclusions about the inversion of the different detectors. They are also indicated in Fig. 5, which shows the depletion voltage as a function of fluence, but with emphasis on the post-rad depletion voltages.

Fig. 5 Depletion voltage as a function of fluence for detectors with different resistivity, low voltages only, scaled to 300 μ m thickness.

The detector with resistivity of 2200 Ω -cm is not inverted after a fluence of $2 \cdot 10^{14}$ HEp/cm². This proves that low-resistivity detectors have inversion at much higher fluence as expressed in eq. 5 and thus can survive much larger radiation fields. It seems clear that there is no clear advantage to using detectors with only moderately low resistivity, like 1.3 k Ω -cm, when compared with high resistivity (6k Ω -cm) detectors. As shown in Fig. 5, both will result with about the same depletion voltage after a fluence of about $2 \cdot 10^{14}$ HEp/cm².

IV. DEPLETION VOLTAGE FROM CHARGE COLLECTION (C-C)

A. Comparison between C-V and C-C

Large currents hampered charge collection measurements after irradiation. For reliable post-rad results, we will have to cool the detectors to keep the currents down. For one detector with resistivity of 1.3k Ω -cm the charge collection was measured pre-rad as a function of bias voltage with a fast front-end amplifier with rise time 20ns designed for ATLAS. The method uses a ⁹⁰Sr telescope as described in Ref. [6]. Figure 6 shows the median pulse height vs. bias. A clear saturation of the charge collection at 4fC is seen. The curve is fit by a square root function (see Eq. (2) above) and intercepts the saturated charge at the depletion voltage of 214V.

Fig. 6 Determination of the depletion voltage from the pre-rad median pulse height as a function of bias voltage (C-C).

Comparing the depletion voltage of 214V from C-C with the C-V depletion voltage of 203V (Fig. 7), we find excellent agreement within 5%.

B. Very High Depletion Voltages

The charge collection (C-C) method can be used to determine the depletion voltage of detectors, pre- or post-rad, with very large depletion voltages, even when the depletion

voltage is out of the reach of the detector bias, in analogy to the C-V method described in Section II.C, Fig. 1. For non-inverted detectors, or more generally for readout of the junction side, the charge collection efficiency has a square root dependence on the bias voltage. Assuming full charge collection at depletion, the pulse height measurement at bias voltages far below the depletion voltage allows the extrapolation to full charge collection efficiency and thus depletion voltage.

Fig. 7 Determination of the depletion voltage for the detector of Fig. 6 from C-V measurements.

The pre-rad charge collection of detector A1 with resistivity of 4300 Ω -cm is shown in Fig.8, where the median pulse height as a function of bias much below the depletion voltage.

Fig. 8 Determination of the depletion voltage from the median pulse height as a function of bias voltage (C-C). The intercept with the saturation value of the charge of 5.2fC occurs at 1100V.

A fit to the data in the small bias voltage range of the measurements shows a square root behavior, and extrapolating to a total charge of 5.2fC for a 390 μ m thick detector, we get a depletion voltage of 1100V, in excellent agreement with the C-V measurements- see Table 1-. Thus the two methods of determining the depletion voltage are equivalent, at least before radiation.

V. CONCLUSIONS

Several silicon strip detectors of resistivity varying from 0.2 to 2.7kOhm were irradiated with 55MeV protons to fluences up to 10¹⁴p/cm².

The depletion voltages were determined both pre-rad and post-rad with C-V measurements. The low resistivity detectors with large initial depletion voltages showed a behavior consistent with much larger inversion fluence than high resistivity detectors.

We find no clear advantage using detectors with resistivity as low as 1 kOhm-cm when compared with high resistivity detectors (6 kOhm-cm). On the other hand, a starting resistivity of less than 500 Ohm-cm leads to higher initial depletion voltage, but delays the inversion beyond the fluence one might encounter at the LHC.

Where the depletion voltages from C-V and charge collection (C-C) could be compared pre-rad, they agreed well.

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VII. REFERENCES

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