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

R. Cannara[1], B. Dezillie[2], T. Dubbs[1], J. Hancock[1], W. Kroeger[1], Z. Li[2], T. Nissen[1], M. Onodera[1,a], W. A. Rowe[1], H. F.-W. Sadrozinski[1], Q.S. Wan[2,b], and L.J. Zhao[2,c]

[1]SCIPP, University of California, Santa Cruz, CA 95064, USA

[2]Brookhaven National Laboratory, Upton, N.Y 11973, USA

Abstract

We have irradiated p-on-n silicon microstrip detectors of initial bulk resistivity between 0.2 and 2.7 kΩ-cm with 55MeV protons to fluences of 0.7, 2 and 11×10^{13} p/cm^2 (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 2×10^{14} p/cm^2 for strips and about 1×10^{15} p/cm^2 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-implants 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 (V_{fd}) of detectors with higher resistivity (≥ 1.2kOhm-cm) could be determined directly from C-V curves, the one for lower resistivity were inferred from plots of $1/C^2$ vs. bias voltage V as follows. Using the plate capacitor equation relating the capacitance C, the area A and the thickness d:

$$C = \varepsilon * \varepsilon_0 * A/d, \quad (1)$$

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

$$V = qN*d^2/(2\,\varepsilon * \varepsilon_0) \quad (2)$$

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

$$1/C^2 = 2/(q*\varepsilon*\varepsilon_0*A^2)*(1/N)*V \;,\; V < V_{fd} \quad (3)$$

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

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

Thus the depletion voltage is determined 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 List of Detectors

	Detector #					
	A1	A2	A4	A3	A5	A6
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 [μm]	390	390	390	295	295	280
Min.Cap C_{min} Prerad [pF]	49	49	49	60	64	61
Dep. Volt. C-V Pre-rad	1100 *	1100 *	2160 *	203	208	100
Dep. Volt. C-V Pre-rad, 300μm	650 *	650 *	1280 *	210	215	115
Dep.Volt C-C Pre-rad	1100 *			214		
Dep.Volt C-C Pre-rad, 300μm	650 *			221		
Dep. Volt. C-V Post-rad		790-890	360-430	85-110	190-220	47-53
Dep. Volt. C-V Post-rad, 300μm		470-530	210-260	89-114	197-227	54-60
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 390micron, their saturated capacitance is expected to be C_{min} = 49pF. 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 micron, which means dividing the measured depletion voltages by a factor $(d/300)^2$, where d is the thickness of the detector in micron.

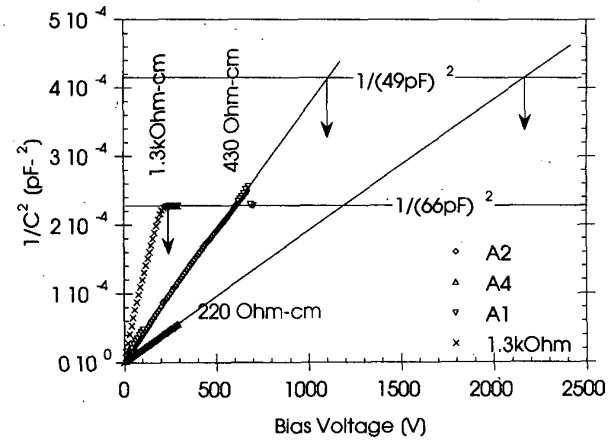

Fig. 1: Pre-rad plot of $1/C^2$ vs. bias voltage for several of the detectors

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 an HP 4281 LCR meter. As outlined above, the quantity $1/C^2$ was plotted as a function of the bias V and the depletion voltage determined as the intercept of the slope proportional to V with a horizontal line corresponding to a constant capacitance C_{min}. This is shown for the irradiated detector A5 in Fig. 2.

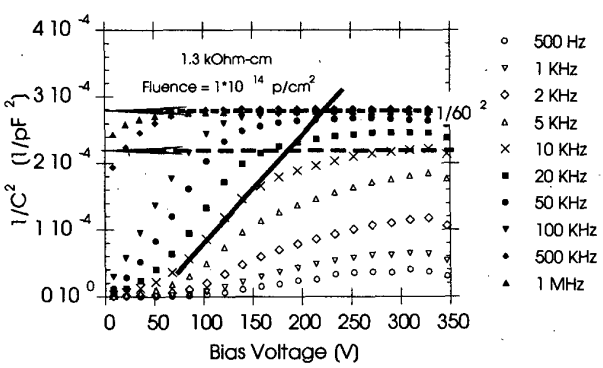

Fig. 2: Plot of $1/C^2$ vs. bias voltage for the irradiated detector A5

As evident in Figure 2, the C-V curves have as 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 sloped line with a horizontal which passes through the highest points in the 10kHz curve as shown in Figure 2, representing the minimum post-rad capacitance. The depletion voltage derived from Figure 2 is 180-210V.

B. Depletion Voltage for different resistivities

Fig. 3 shows the depletion voltage of all detectors as a function of high-energy proton fluence, where the depletion voltage is normalized to a 300micron 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 reflect the uncertainty in the determination of the depletion voltage for the frequency of 10kHz. Data for the highest HE proton fluence of about $2.2*10^{14}$ 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 the detector with higher resistivity is inverted, while the one with lower resistivity is not.

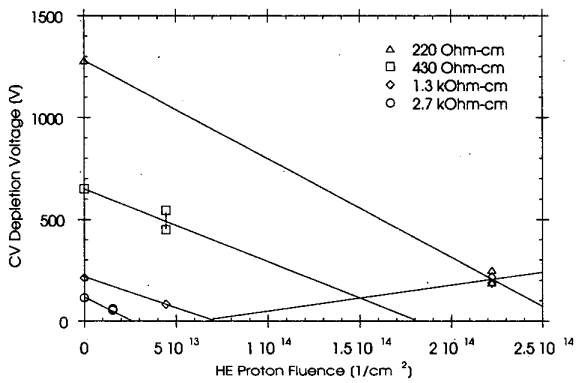

Fig. 3 Depletion voltage as a function of fluence for detectors with different resistivity, scaled to 300micron thickness.

Figure 3 shows straight lines motivated by the findings of the Rose Collaboration [2,3], that the inversion fluence Φ_{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 $N_{eff,0}$ [3]. We find as an approximate relation:

$$\Phi_{inv}=13* N_{eff,0} \quad (5)$$

C. Establishing 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 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 [5]. For non-inverted detectors, the initial doping concentration dominates the effective doping concentration leading to a shallow maximum in the time dependence of the depletion voltage. Inverted detectors show to a pronounced minimum after a few days of annealing. The RT annealing curves are shown in Fig. 4 for all five irradiated detectors: only detector A5 detectors with resistivity of 1.3k Ohm-cm is clearly inverted at the highest fluence.

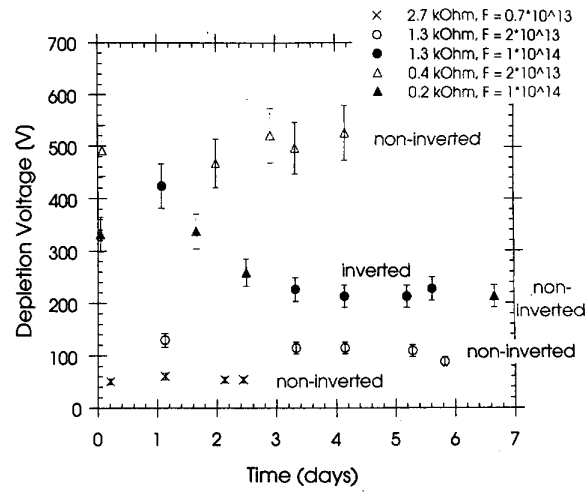

Fig. 4: Depletion voltage as a function of RT annealing time for all five irradiated detectors, scaled to 300micron thickness.

The lines in Fig. 3 and, for lower voltages, Fig. 5 take into account the annealing behavior, and our conclusions about weather the detectors are inverted. Fig. 5 also shows the expected depletion voltage for high resistivity detectors [5].

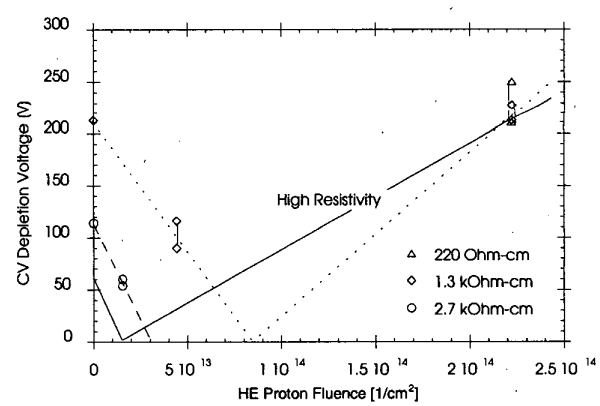

Fig. 5: Depletion voltage as a function of fluence for detectors with different resistivity, low voltages only.

The detector A4 with resistivity 220 Ohm-cm is not inverted after a fluence of $2*10^{14}$ HE p/cm^2. 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 real advantage to using detectors with only moderately low resistivity, like 1.3 kOhm-cm, when compared with high resistivity (~6 kOhm-cm) detectors. As shown in Fig. 5, both will end up with about the same depletion voltage after a fluence of about $2*10^{14}$ HE p/cm^2.

IV. Depletion Voltage from Charge Collection (C-C)

A. Comparison between C-V and C-C

Large leakage currents hampered post-rad charge collection measurements. For reliable post-rad results, we will have to cool the detectors to keep the currents down. For detector A3 with resistivity 1.3 kOhm-cm the charge collection was measured pre-rad as a function of bias voltage with a fast front-end amplifier with a rise time of 20ns designed for ATLAS. The method uses a 90 Sr telescope as described in Ref [6]. Figure 6 shows the median pulse height vs. bias voltage for detector A3. A clear saturation of the charge collection at 4fC is seen. The curve is fit by a square root curve (see Eq. 2 above) and intercepts the saturated charge at the depletion voltage of 214V.

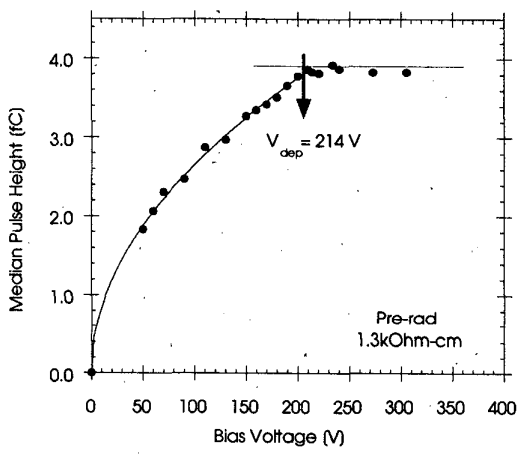

Fig. 6: Determination of the pre-rad depletion voltage of detector A3 from the median pulse height as a function of bias voltage (C-C).

Comparing the depletion voltage 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 beyond the reach of the detector biasing, 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. The depletion voltage is then the intercept of this square root curve with the horizontal line after constant charge collection efficiency is reached after depletion, here assumed to be 100%.

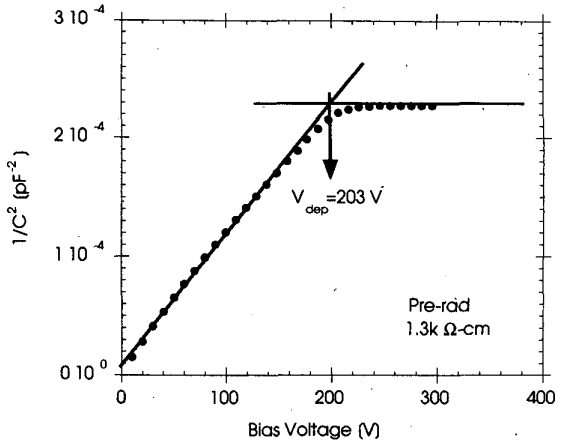

Fig. 7: Determination of the pre-rad depletion voltage from C-V measurements for detector A3.

The pre-rad charge collection of detector A1 with resistivity of 430Ohm-cm is shown in Fig.8, where the median pulse height as a function of bias much below the depletion voltage is fitted. In the small bias voltage range of the measurements, the data shows a square root behavior, and extrapolating to a total charge of 5.2fC for a 390micron 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.

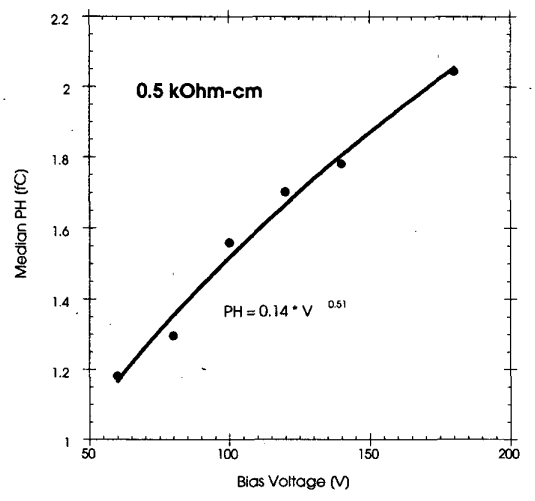

Fig. 8: Determination of the depletion voltage from the median pulse height as a function of bias voltage (C-C). The intercept with the saturation value of the charge of 5.2fC occurs at 1100V.

V. CONCLUSIONS

Several silicon strip detectors of resistivity varying from 0.2 to 2.7kOhm were irradiated with 55MeV protons to fluences up to 10^{14}p/ cm^2.

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 1kOhm-cn when compared with high-resistivity detectors (6kOhm-cm). However, we note that there are only limited measurement points for all samples after inversion and that β, the rate of change of the effective doping density after inversion, seems to be different for the different resistivity samples. Other work [7] did find similar β values for various resistivities, which would offer some advantage for low ρ even after inversion in the modest fluence range. 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 extracted from capacitance measurements (C-V) and charge collection (C-C) can be compared directly (pre-rad), they show good agreement.

VI. ACKNOWLEDGMENTS

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VII. REFERENCES

Permanent address:

[a] Redwood Middle School, Saratoga, CA 95070

[b] Northwest Nuclear Research Institute, P. R. China,

[c] Inst. of Semi, P. O. Box 912, Beijing 100083, P. R. China

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