Studies of Ionizing Radiation Effects on Silicon Drift Detectors

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Abstract

A 45x45 mm rectangular Silicon Drift Detector (SDD) was irradiated using a Co^{60} γ-source and its performance was studied. The total integrated dosage was 9 krad which is equivalent to the ionizing radiation dosage that the STAR SVT inner barrel detectors are expected to receive during 10 years of running at the soon to be built RHIC collider. The detector's performance after a high temperature annealing was also studied. The detector was found to be sufficiently radiation hard for RHIC applications.

1 Introduction

The Silicon Drift Detector (SDD) is a charged particle position measuring device with position resolution of the order of 10 μm in each coordinate[1]. A charged particle crossing the detector leaves a trail of electron-hole pairs along its path. Holes are immediately absorbed by the cathodes on the surface of the detector, while electrons converge to the middle of the bulk and drift toward the anodes at a constant speed under the influence of an applied uniform E-field. One coordinate of the particle position is determined from the drift time while charge division between anodes gives the other coordinate.

Future collider experiments will take place in high luminosity machines such as the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC). Silicon detectors are expected to track charged particles close to the collisions and provide vertex information. Being close to the beams they will encounter high radiation doses and it is therefore important that these detectors are radiation hard.

The goal of the present work was to irradiate a prototype STAR SDD (designated "STAR-1") to study its radiation hardness for a RHIC-type environment. To what degree the detector is radiation hard is tested by carrying out laser measurements of its drift characteristics (e.g. time versus position and pulse width versus position) after irradiation. The SDD was exposed to doses of up to 9 krad from a Co^{60} γ-source over a period of one day and drift times, amplitudes, the sigma of the electron cloud, leakage currents, surface interface charge densities and cathode voltages were measured. This exposure is expected to be equivalent to 10 years of running at the RHIC collider.

2 Experimental Procedure

The measurements were made using one of the STAR-1 4.5 cm x 4.5 cm rectangular one-way drift SDD's having 178 anodes at 250 μm pitch and 332 cathodes at 120 μm pitch. They were made out of 3" diameter 8 kΩ·cm N-type NTD Silicon wafers with (111) crystal orientation. Figure 1 shows a schematic diagram of a STAR-1 detector. The operation of the detector has been described in detail elsewhere[2].

Drift time and pulse width versus position measurements were carried out at The Ohio State University using the apparatus shown in Figure 2.

This technique is well known[3]. Charged particle hits were simulated using a Nd:YAG laser of wavelength 1.064 μm, just above the band edge where silicon becomes transparent. The laser pulse duration was 8 ns. The size of the laser spot on the surface was about 20 μm which does not introduce any additional uncertainty in the drift position since it is small compared to the natural charge cloud spread due to the Coulomb repulsion and diffusion. The nominal drift field applied was 450 V/cm. After passing though a preamp and a shaper the data is read out via a 200 MHz Nicolet digital oscilloscope.

The laser amplitude was attenuated to deposit the same amount of energy as a minimum ionizing particle. The calibration was done using a Pa^{234} source (E_{β}=2.29 MeV). The laser has 20% pulse-to-pulse amplitude fluctuations. For this reason averages over 10 waveforms were taken to reduce errors in amplitude measurements. A typical waveform is shown in Figure 3 and is seen to be close to a gaussian.

The SDD was irradiated using a 3 kCi Co^{60} γ-source at The Ohio State University Nuclear Reactor Laboratory. Since the primary effect from the ionizing radiation is to increase the the fixed oxide volume charge density ρ_{ox}, and, to a lesser degree, the silicon-oxide interface charge density σ_{ox} both of which are heavily influenced by the biasing conditions, the detector was kept biased during the irradiation. In addition, several MOS capacitors, made from the same wafer as the SDD and biased at -40V with respect to the substrate, were irradiated simultaneously to allow one to measure flatband voltages as a function of the dosage and hence to measure changes in ρ_{ox} and σ_{ox}.

The detector was irradiated 3 times over a 1 day period. Initially the detector was given a 815 ± 40 rad dose in 10 minutes and measurements were made 2 hours later. After 5 hours from the initial irradiation another 3625 ± 180 rad was applied and measurements made 4 hours later. Finally, 16 hours after the second irradiation an additional 4600 ± 230 rad was applied making a total of 9040 ± 300 rad. Measurements were made 2 days after the last irradiation to allow for the 40 hour room-temperature annealing process to complete[4]. The detector was then annealed for 1 hour at 70^0C and measurements were made again. A final high-temperature annealing (1 hour at 110^0C) was carried out later. In total six sets of laser measurements were made: 1) before irradiation as a baseline, 2) after about 1 krad irradiation, 3) after about 4.6 krad irradiation, 4) after about 9 krad irradiation, 5) after the low-temperature anneal, and 6) after the high-temperature annealing.

3 Data and Results

Figure 4 shows drift times versus distance from the anodes for four of the measurements mentioned above. Measurement 2 showed little change from measurement 1 and is not shown. In Figure 4a the baseline performance of the detector is seen before irradiation. The detector used in this test is seen to be linear except for a jump occurring at about 5 mm from the anodes. This jump is caused by a non-uniformity in the implanted resistive divider on the detector. Since we were primarily interested in changes in the performance of the detector, this detector was judged to be adequate for the present irradiation tests. After the 4.6 krad irradiation (Figure 4b) the detector was not affected significantly, but after 9 krad (Figure 4c) electrons would not drift beyond about 5 mm. Following the high-temperature anneal, however, the detector seemed to have practically recovered to its original baseline performance (Figure 4d). After the high-temperature anneal the current through the resistor divider chain implanted on the silicon chip increased so measurements in Figure 4d were made at a lower drift field (300 V/cm). Hence slopes and the jump at 5 mm appear larger.

The difference in drift time from a linear fit to the data versus distance is shown in Figure 5. As seen there is some substructure which is caused by nonlinear drift fields. These do not change in magnitude with the applied irradiation and can be either reduced by different fitting procedures or tuning the applied drift field.

Figure 6 shows the pulse width, σ, versus distance. The jump in σ at about 5 mm is due to the drift field distortions caused by the resistor defect mentioned above[5]. The width (σ of a gaussian fit) of the cloud decreases with increased dosage as seen in Figure 6b. However, after the high-temperature anneal σ increases once again. The reduced drift field used after the high-temperature anneal can only account for 22% of the increase. The signal amplitude also decreases by about 50% after the 9 krad irradiation compared to the baseline measurement, though it recovers to 75% of its baseline value after the high-temperature anneal. It is interesting to note that no significant improvement was observed after a prior low temperature (1 hour at 70^0C) anneal.

The signal RMS noise remained constant at under 10 mV. No statistically significant changes in bulk and surface leakage currents were observed. In addition the position resolution, determined by the accuracy with which one can determine the peak position, remained constant over the irradiation process at about 20 μm at a distance of 0.25 cm from the anodes.

The MOS capacitor measurements indicate that the flatband voltage increased by 4.4 ± 0.15V for each krad received from the initial value of 8V. This is due to an increase oxide volume, and, to a lesser degree, interface charge densities.

4 Discussion

As mentioned above (see Figure 4c), after the final 9 krad dosage it was noticed that one could not drift past 5 mm. This is thought to be due to a drift field direction reversal between cathodes 40 and 41 caused by a current path between two guard strips at the edge of the detector induced by ionizing radiation. Figure 7 shows the cathode strip voltage versus cathode strip number for a) no irradiation, b) 4.6 krad, c) 9 krad and d) after the high-temperature anneal following the 9 krad irradiation. By comparing Figure 7c with the other cases near cathode #40, the potential drop corresponding to the field reversal can be seen.

Figure 8 shows how the field reversal might have occurred. Cathode 40 is bonded to the external voltage divider while 41 is connected to one of the guard strips which could have a current path with the guard strip connected to cathode 37 which was biased at a lower potential than cathode 41 thus "pulling" 41 well below its intended bias level. Figure 9 shows a plot of potential difference between cathodes 40 and 41 as a function of the applied high voltage (HV). Ideally, this ΔV should increase linearly as a function of HV, but instead, as can be seen from this figure, it becomes negative at around 700V.

Cathodes 20-21 and 60-61 have identical arrangements as the 40-41 pair, and these pairs are found to have the same kind of problem: 20-21 also has an inversion, although not as severe as 40-41 (-1.5V compared to -5.6V on the 40-41 pair). The 60-61 pair does not have an inversion, but ΔV for this pair is still significantly lower than that on the neighboring cathodes (Fig. 7c). The newer STAR SDD prototypes (starting with STAR-2) should not have this problem, since the guard strips there will be simple aluminum field plates on the oxide surface (there will be no p^+ implants beneath them).

It is believed the high-temperature anneal puts electrons into the newly created (as a result of the irradiation) positive interface states thus making them neutral but not eliminating them. These detectors are hence more sensitive to further irradiation. Further, this might explain the recovery from the drift field reversal observed after the 9 krad irradiation.

5 Conclusions

It is seen that Silicon Drift Detectors should be sufficiently radiation hard to ionizing radiation for RHIC applications and should be able to withstand a 10 year running period at RHIC. Further, a high-temperature anneal is shown to restore the detector to its baseline performance.

6 Acknowledgements

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[5] G. Vilkelis, Star Note (to be submitted) 1994.

Figure 1: *Schematic diagram of a STAR-1 detector.*

Figure 2: *The apparatus setup showing a Nd:YAG laser depositing charge onto a silicon wafer.*

Figure 3: *The waveform from the shaper for a laser pulse 0.5 mm from the anodes.*

Figure 4: *Drift times versus distance from the anodes.*

Figure 5: *Difference in drift time from a linear fit to Figure. 4 versus distance.*

Figure 6: *Width (σ) of the waveform versus distance.*

Figure 7: *Voltage distribution on the cathodes.*

Figure 8: *Sketch of the region where the shortcircuit causing the ΔV inversion between cathodes 40 and 41 occurs.*

Figure 9: *ΔV between cathodes 40 and 41 versus applied high voltage.*

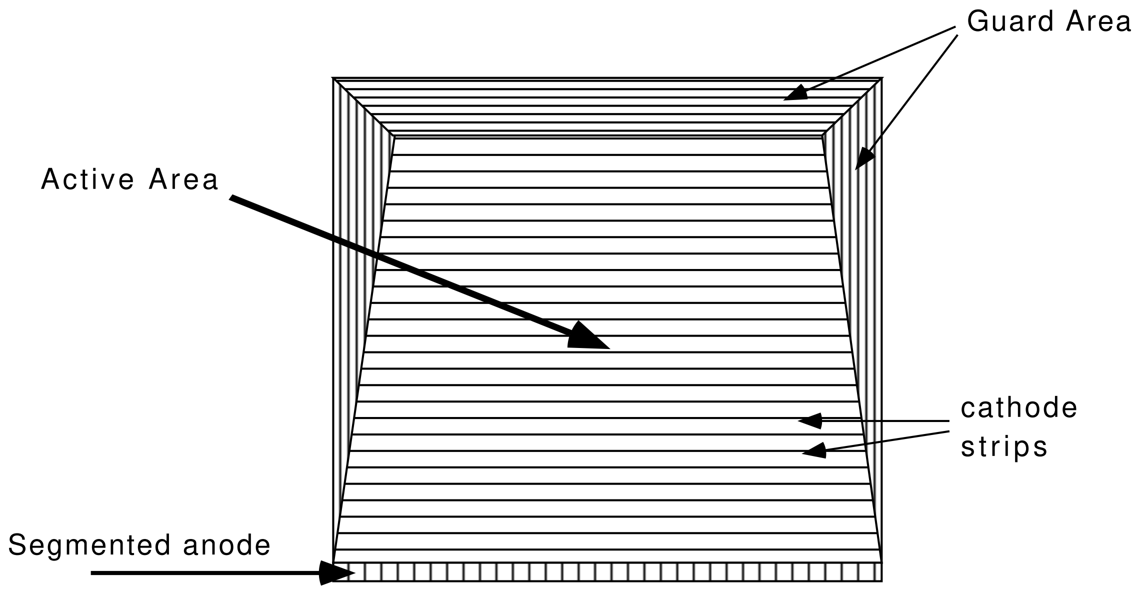


Figure 1:

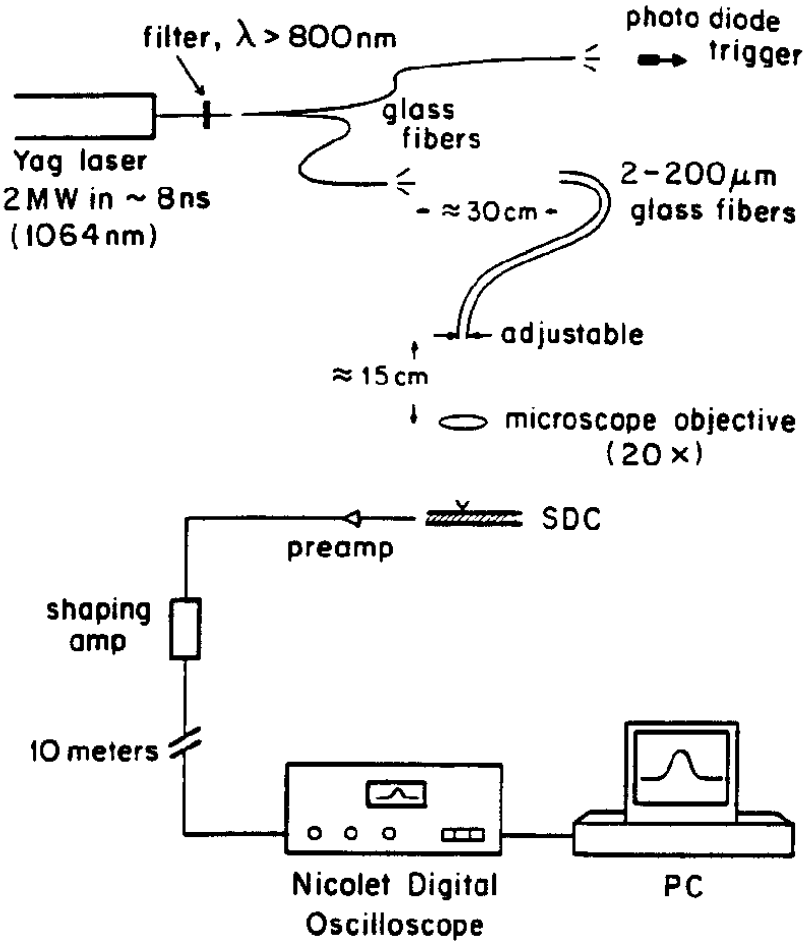

filter, λ > 800nm
photo diode
trigger
glass
fibers
Yag laser
2MW in ~ 8ns
(1064nm)
≈ 30cm
2-200μm
glass fibers
adjustable
≈ 15cm
microscope objective
(20×)
SDC
preamp
shaping
amp
10 meters
Nicolet Digital
Oscilloscope
PC

Figure 2:

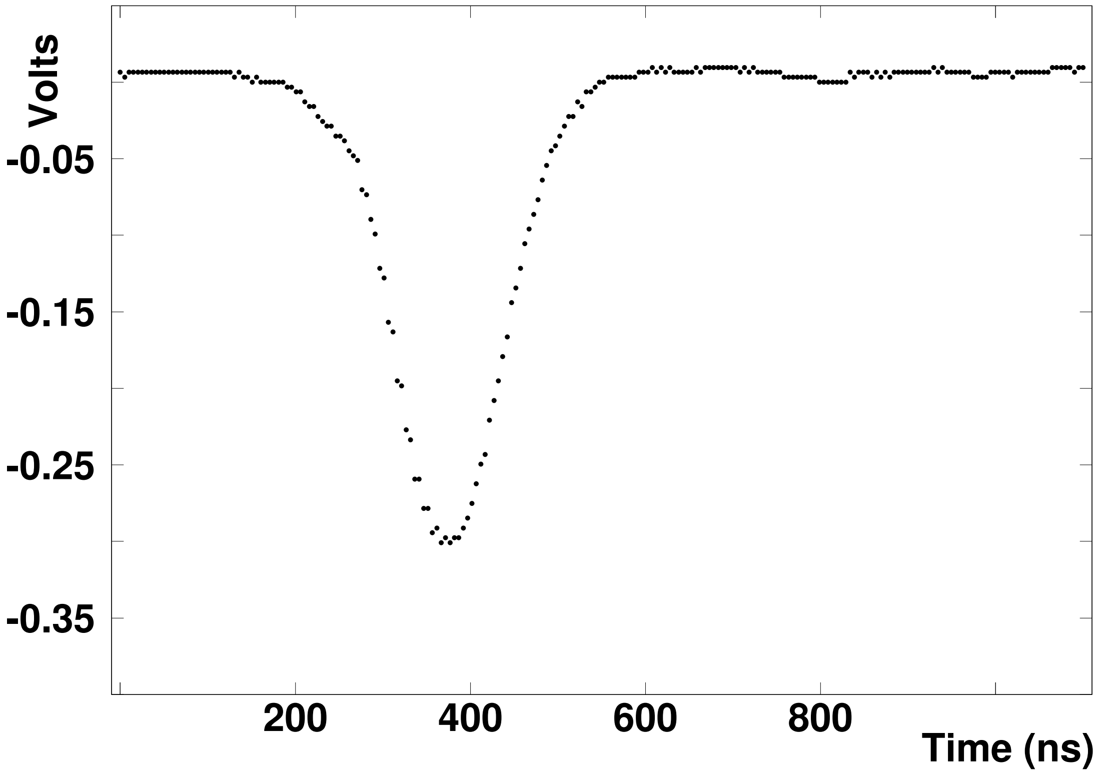


Figure 3:

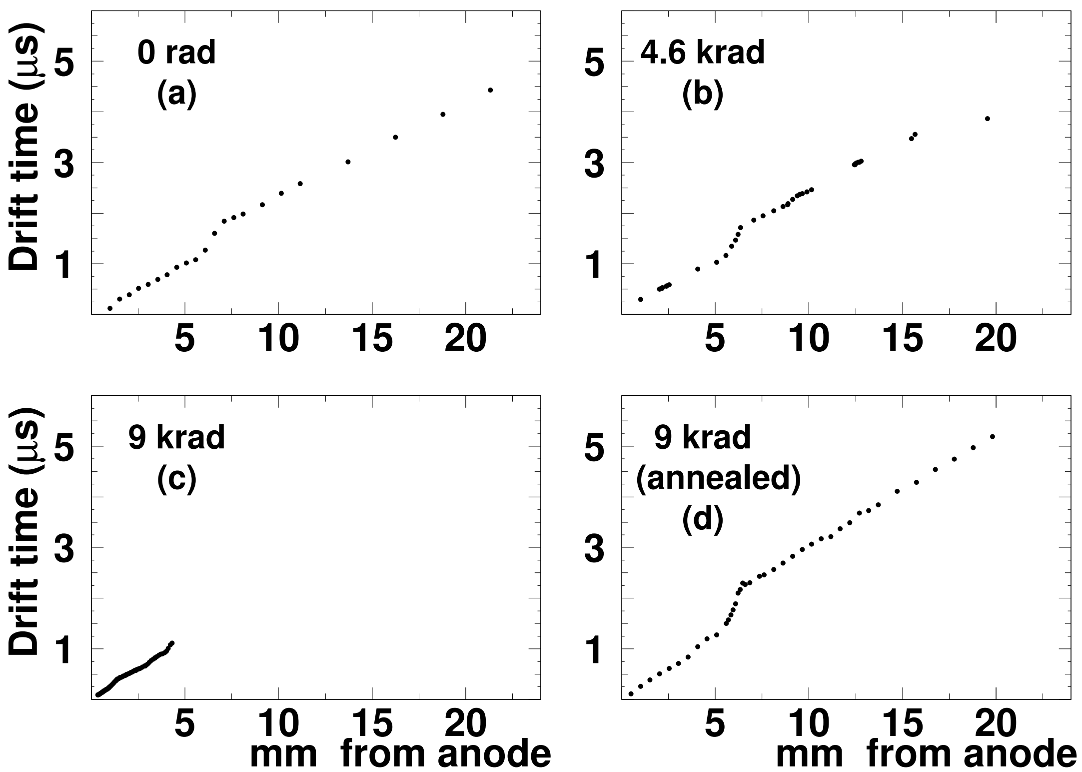

Drift time (μs)
0 rad
(a)
4.6 krad
(b)
9 krad
(c)
9 krad
(annealed)
(d)
mm from anode

Figure 4:

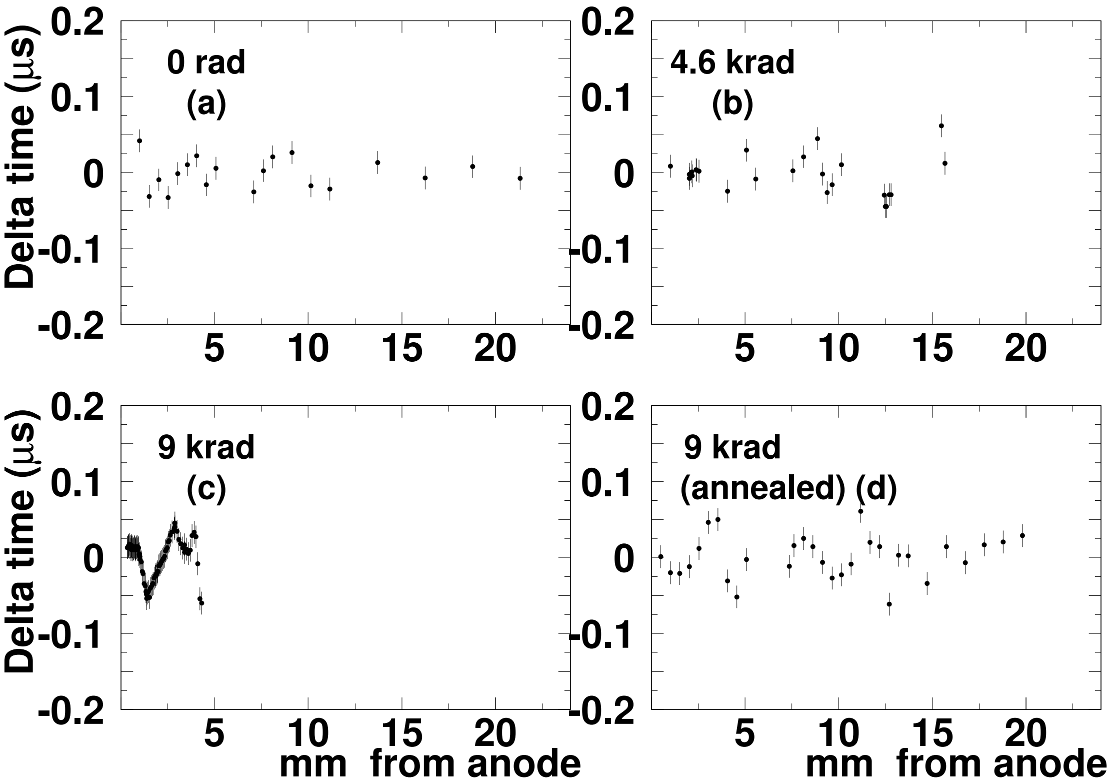
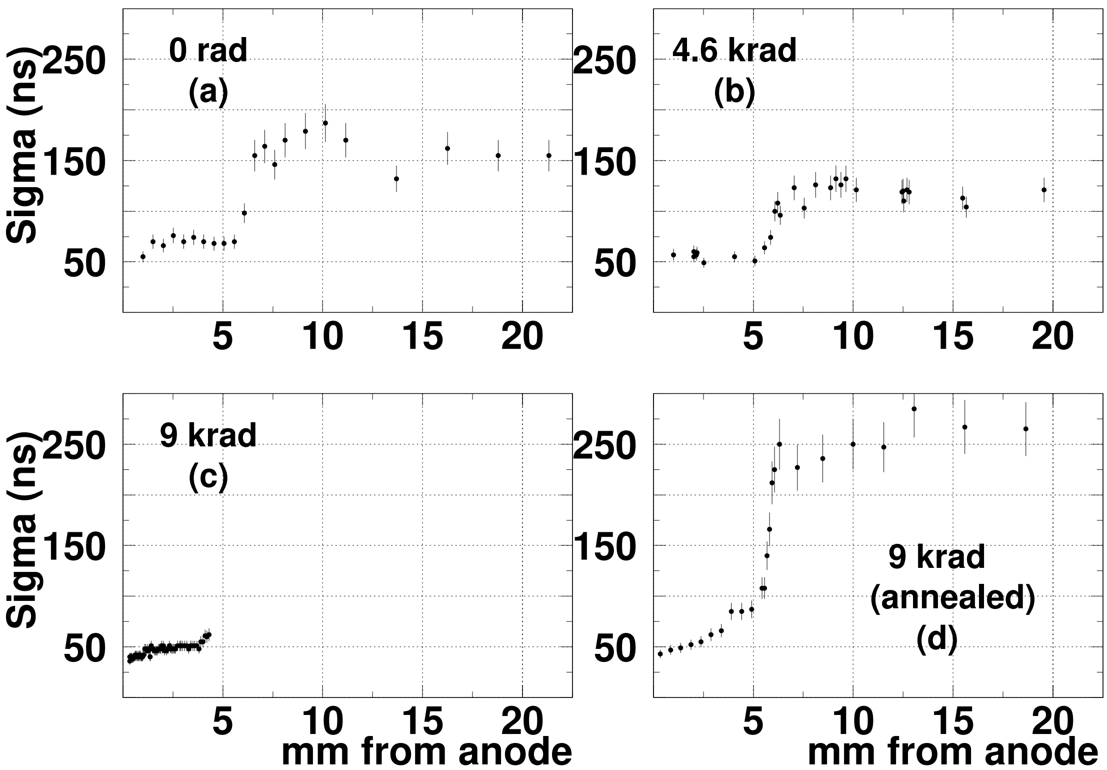
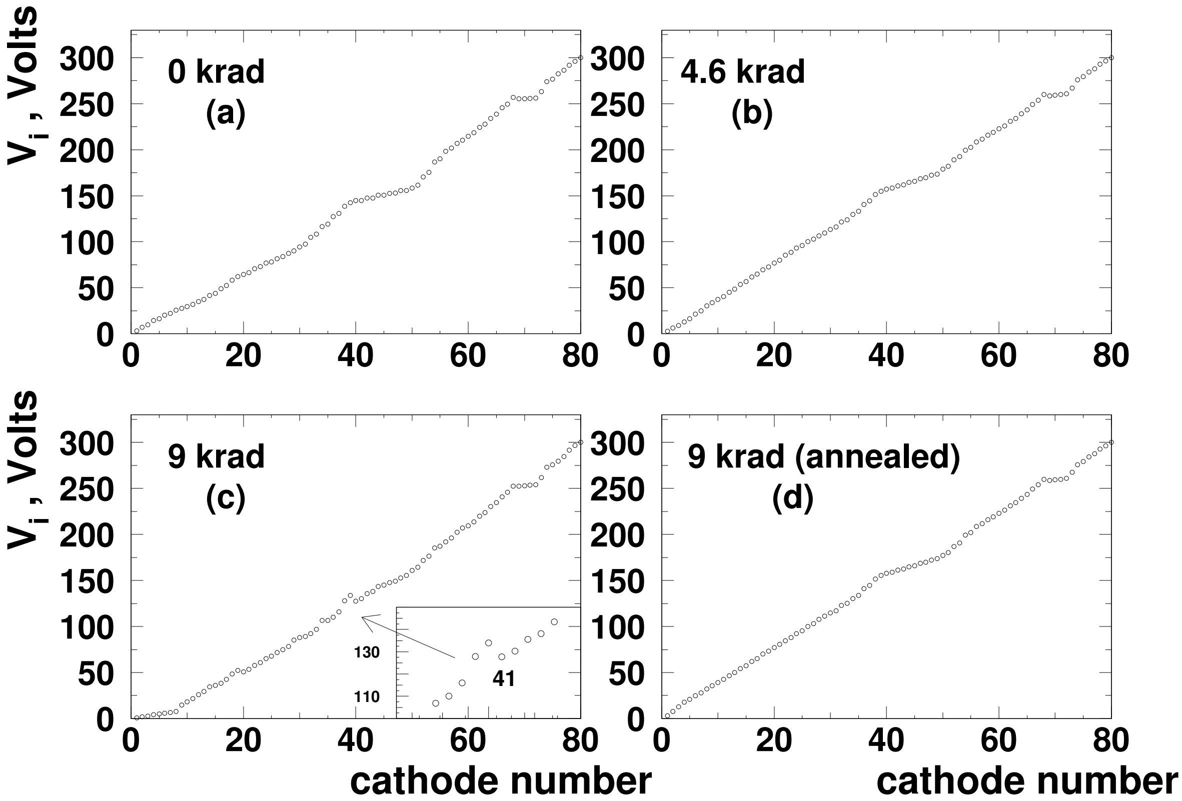

Delta time (μs)
0.2
0.1
0
-0.1
-0.2
0 rad
(a)
4.6 krad
(b)
9 krad
(c)
9 krad
(annealed) (d)
5
10
15
20
mm from anode

Figure 5:



0 rad
(a)
4.6 krad
(b)
9 krad
(c)
9 krad
(annealed)
(d)
Sigma (ns)
250
150
50
5
10
15
20
mm from anode

Figure 6:



V_i , Volts
0 krad
(a)
4.6 krad
(b)
9 krad
(c)
9 krad (annealed)
(d)
130
110
41
0
50
100
150
200
250
300
0
20
40
60
80
cathode number

Figure 7:

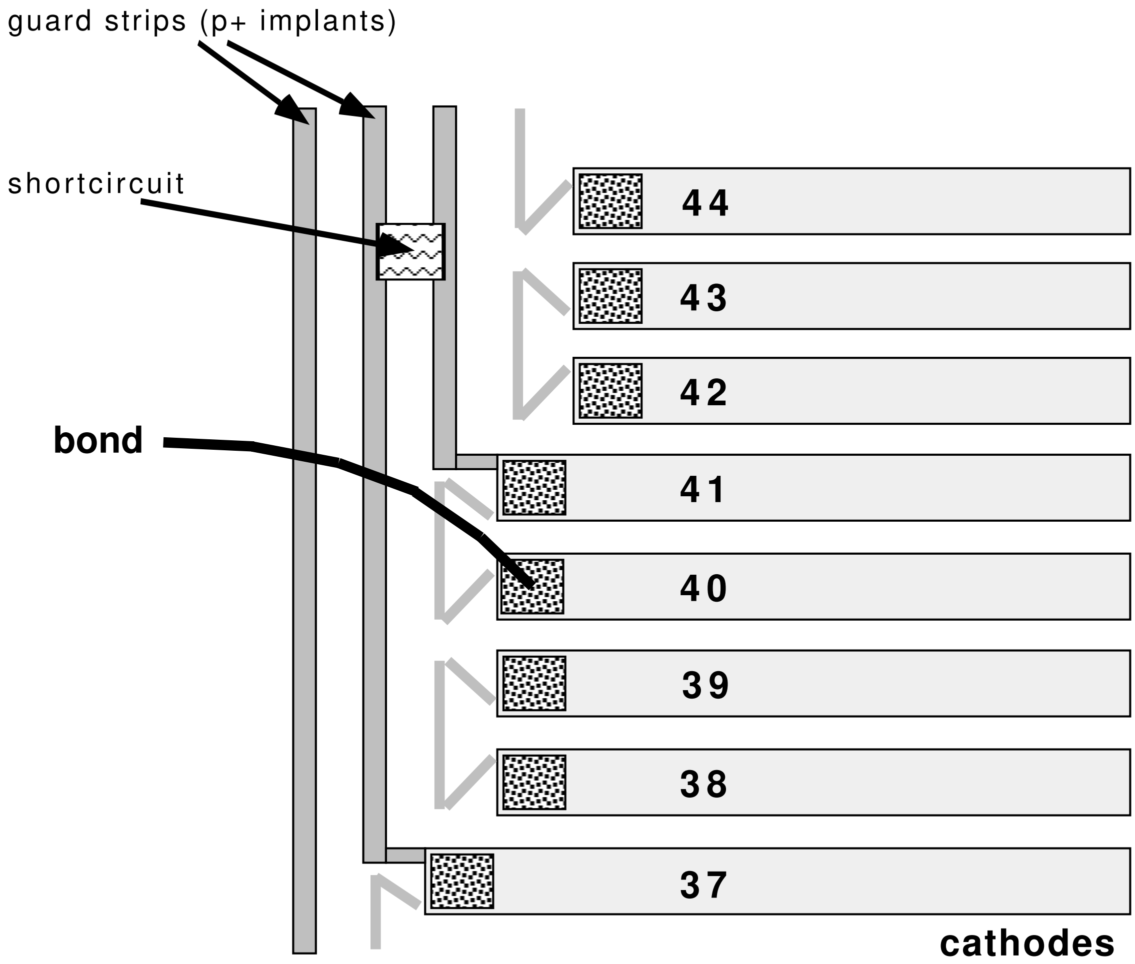
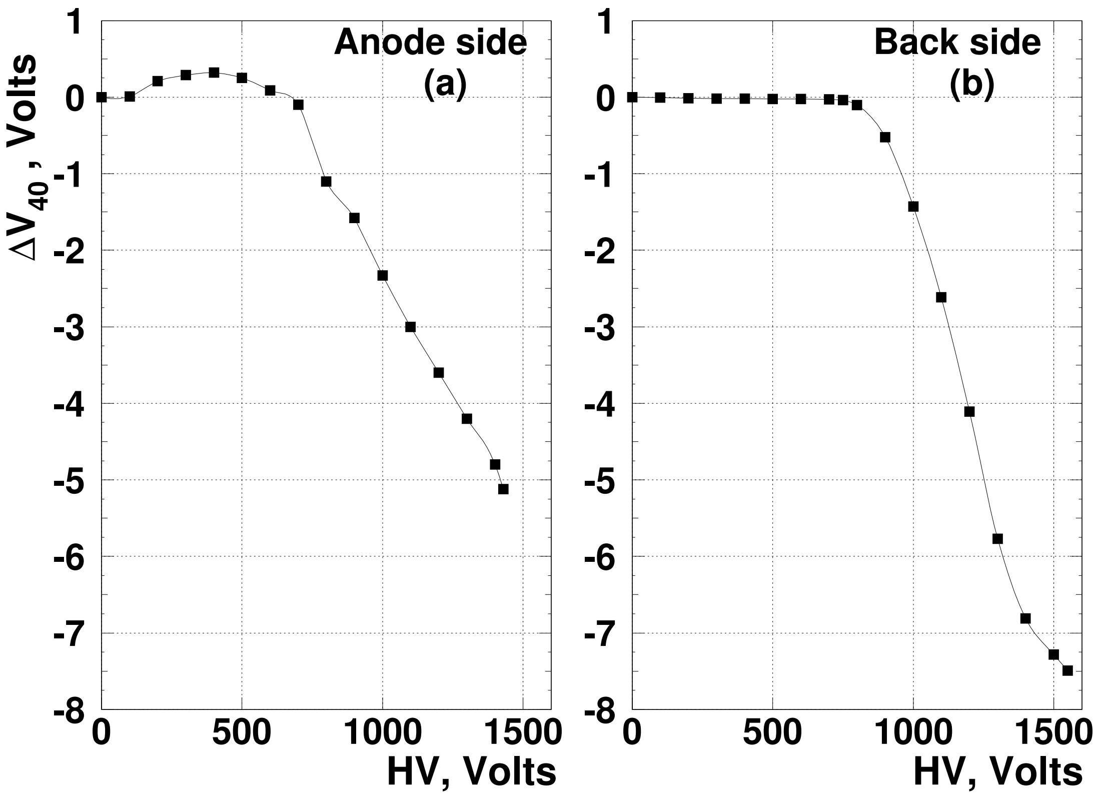

guard strips (p+ implants)
shortcircuit
bond
44
43
42
41
40
39
38
37
cathodes

Figure 8:



Anode side
(a)
Back side
(b)
ΔV_{40} , Volts
HV, Volts
HV, Volts
1
0
-1
-2
-3
-4
-5
-6
-7
-8
0
500
1000
1500

Figure 9: