Characterization of Pre- and Post-Gamma Irradiated Mini Silicon Strip Detectors

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by

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Abstract

This paper will cover the pre- and post-irradiation characterization of several gamma irradiated mini SSDs. Characterization measurements used included current-voltage and capacitance-voltage test which used cooling and nitrogen to increase stability. Strip specific tests were also conducted to elucidate the origin of several issues which arose during testing. Two irradiations took place, once with the strips of each mini SSD biased, and once without any bias on the mini SSD. We will discuss the results of these tests after covering the experimental setups used, and future test considerations will be proposed.

Acknowledgments

I would like to extend thanks to David Lynn at Brookhaven National Laboratories for his assistance irradiating these mini SSDs. I would also like to thank Professor Hartmut Sadrozinski for his guidance and help over my undergraduate career - I could not have asked for a better advisor. Thanks are also well deserved by my fellow lab workers, who made work enjoyable and were always helpful. Finally, I want to thank my parents. Without their care and support none of this would have been possible.

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1. Introduction

Background

Silicon strip detectors (SSDs) are the detector of choice in high energy particle physics due to their fast response times, high accuracy, and thin profile. The mini SSDs are typically composed of bulk doped silicon, which has oppositely doped strip implants on the surface. As a charged particle passes through the bulk it creates free electron-hole pairs. These electrons/holes are accelerated towards the strip implants where they are collected and signal the event to the connected electronics. The event can then be reconstructed using the strip number to determine location and the timing. When multiple mini SSDs are combined the path of the particle can be reconstructed.

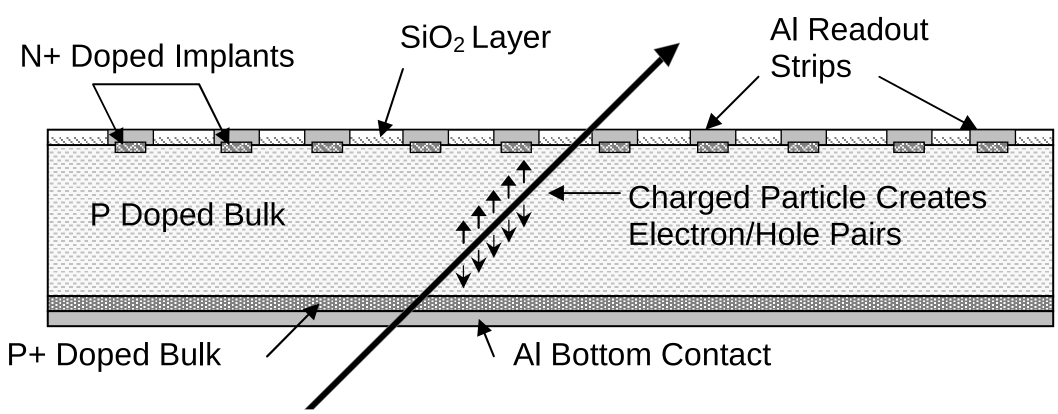

Figure 1.1: N-on-P Mini SSD.

There are many varieties of mini SSDs, which can be broken down into three main categories: silicon growth method, doping and geometry. We will be looking specifically at Float Zone (FZ) growth silicon, which is grown with oxygen inside the crystal as it has been shown to increase radiation hardness [1]. In addition, we will be looking at N-on-P doped mini SSDs manufactured by HPK within the Atlas collaboration. As such, these mini SSDs represent a fairly small segment of the total possible mini SSD configurations. However, the mini SSDs in this manufacturing group also came in several different zones, or modified testing geometries.

Motivation

The Large Hadron Collider (LHC) High Luminosity Upgrade, otherwise known as the superLHC, is a project which will upgrade the LHC luminosity by one order of magnitude while still maintaining its current resolution and physics performance. Our efforts are focused on researching which silicon detectors will be most suitable for the upgrade. It is important that we maintain the performance of these mini SSDs despite the much higher levels of radiation damage the mini SSDs will be subject to. Increased radiation damage is a large factor in determining the next line of mini SSDs which will be used in the superLHC, therefore, the study of gamma radiation damage to mini SSDs is the focus of this experiment. Pre- and post-irradiation testing is done in order to gauge the mini SSDs ability to withstand damage.

2. Experiment

Outline

This experiment consisted of gamma irradiating mini SSDs of various types to judge how their performance depended on gamma irradiation exposure. We tested N on P FZ mini SSDs, of which we explored three different geometries (zones 1, 3 and 4). Zone 1 had no punch through protection structure and required p-stop, zone 3 had a narrow common between strips and p-stop, and zone 4 had a narrow common with punch through protection structures. The mini SSDs were submitted to current-voltage (I-V) measurements which helps characterize their breakdown voltage, an important factor in determining the amount of damage the mini SSD received as well as its operational limits. We also performed other tests of performance, including capacitance-voltage (C-V) before irradiation. After these initial tests, they were packaged and shipped to be gamma irradiated by David Lynn at Brookhaven National Laboratories. The irradiation was done up to 1 Million rads, in two sets. The first set was composed of five mini SSDs which were biased during the irradiation. The second set was composed of three more mini SSDs, which were not biased during the irradiation. Post-irradiation each mini SSD was subjected to several I-V tests along with temperature controls and exposure to nitrogen gas. In addition, C-V and selected strip testing was conducted on select mini SSDs. Next we cover the specific setup of our I-V and C-V testing, followed by the irradiation setup.

Current-Voltage and Capacitance-Voltage Setup

Characterization of mini SSDs using I-V allows the breakdown voltage of a mini SSD to be determined with minimal effort. This voltage is defined as the point where the current increases by at least 0.125 micro-amps over a 50 volt step. All mini SSDs are submitted to this simple test to verify that they are operational before any further experiments are done on them.

The test begins with placing the mini SSD inside a probe station which is sealed and made light-tight. The mini SSD is placed on a larger piece of G10 (insulated copper plate), which could also be a peltier device for precise cooling. Suction is used to hold the mini SSD in place, along with tape if needed. This sits on top of a chuck which contains liquid cooling for heat removal if required. A plastic container with an open top is placed over the mini SSD which can also be pumped with Nitrogen gas to create a dry air environment, to prevent condensation and freezing on the surface of the mini SSD.

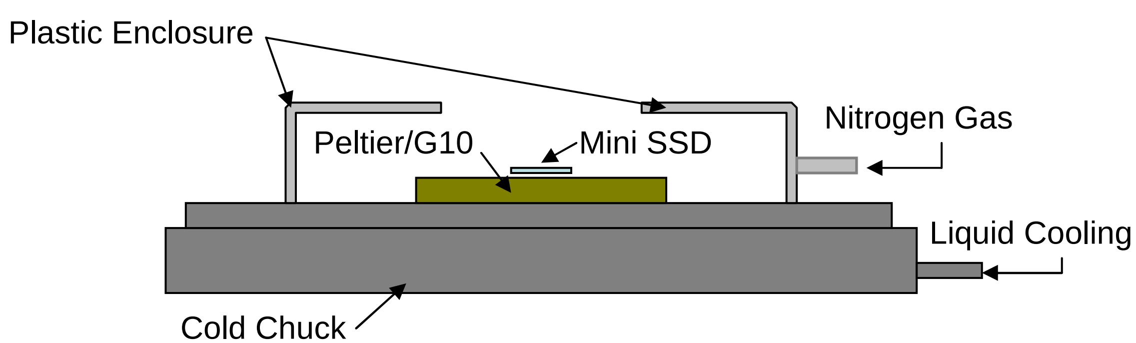

Figure 2.1: Probe station Diagram.

Finally, probes are used to touch down on the mini SSD. In the case of a simple I-V only two probes are needed, one for the G10 for the high voltage bias, and one to ground the bias ring [Fig. 2.2]. A third probe was also used to ground the strips to the bias ring in some experiments as well [Fig. 2.3].

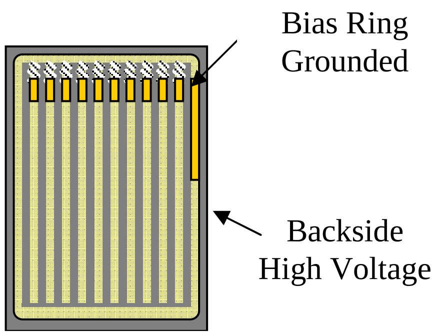

Figure 2.2:
I-V – Strips Not Grounded.

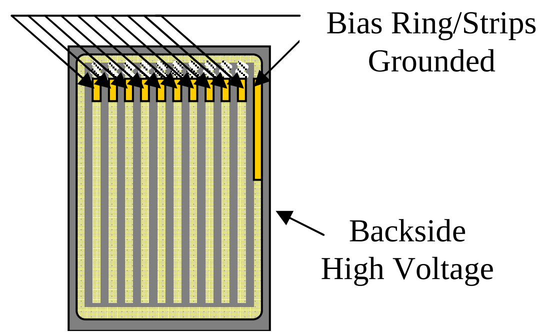

Figure 2.3:
I-V – Strips Grounded.

The probes are connected via BNC cables through a breakout box from inside to outside of the probe station, and connected to a Keithley high voltage power supply and current meter, which is rated up to 1100 volts. The Keithley power supply is then controlled through the use of an automated data acquisition program (ADAP), which helps to ensure voltage steps are made at uniform time steps and streamline data analysis.

The C-V measurements use the I-V measurement template and the same probe and station setup. However, once connected the high and low voltage probes are connected through an HP 16065A Ext Voltage Bias Fixture which converts between an AC and DC signal, which is then fed into an Agilent Precision LCR meter. We use ADAP to automate the data acquisition here as well. Frequency is also varied in these tests to determine frequency dependencies.

Pre-Irradiation Results

Current-Voltage Results

Typical pre-rad current over all mini SSDs was under 10 nA, and breakdown was seen between 700 and 1100 volts. These values were not the best representation of these mini SSDs, which typically have low current and high breakdown voltages, as the bext batch had a problem with their masking fixed and all had breakdown at greater than 1,000 volts. A graph of all mini SSDs in this experiment is included below, with open symbols used to distinguish mini SSDs which were to be irradiated without bias [Fig. 2.4].

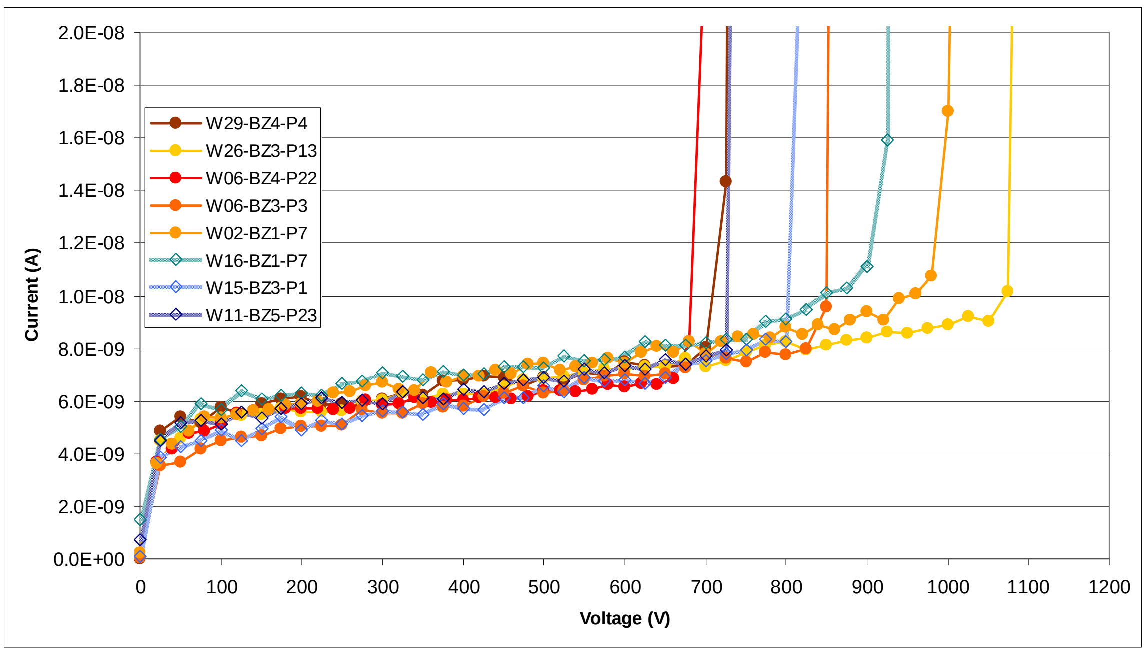

Figure 2.4: Pre-Radiation I-V of all mini SSDs.

Capacitance-Voltage Results

The pre-radiation C-V results were similar to the I-V results pre-rad, and very uniform. The $1/C^2$ curves flatten at around 160 volts signifying full depletion of the mini SSD [2]. All mini SSDs are shown at 10kHz and 100kHz [Fig. 2.5 and 2.6].

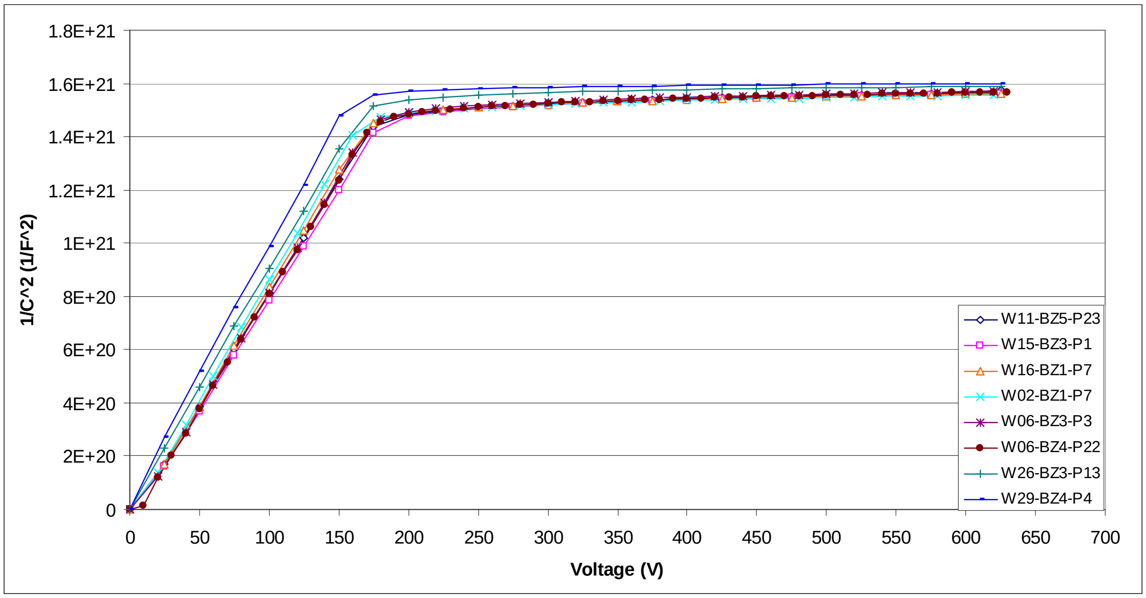

Figure 2.5: $1/C^2$ @ 10kHz, all mini SSDs.

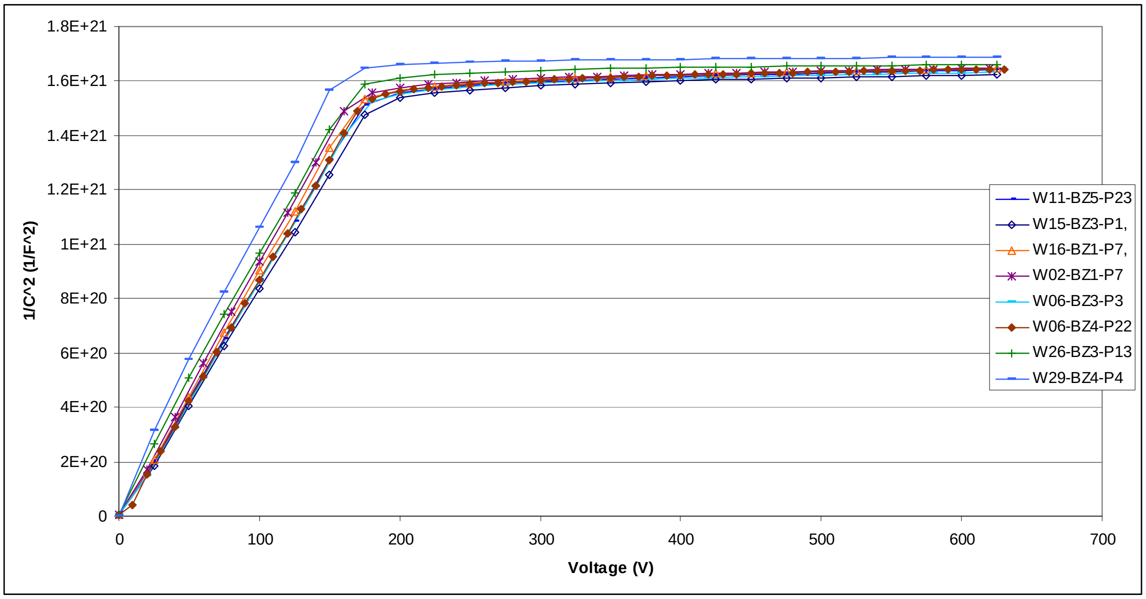

Figure 2.6: $1/C^2$ @ 100kHz, all mini SSDs.

Irradiation Setup

In order to test the effects of grounding the strips on these mini SSDs, as opposed to leaving them floating, several extra steps had to be taken throughout the experiment. The mini SSDs had to first be glued down to small strips of G10 for support and a place to attach wire bonds. We applied conductive epoxy along with the glue in order to provide an electrical contact for biasing the back of the mini SSD. A gold pad which was insulated from the G10 surface was then attached, and all strips were wire bonded from their DC pad to the gold pad. Similarly, this was done for the bias ring to a separate gold pad. Doing this allowed the mini SSD to be biased along with all the strips with a minimal number of micro-positioner probes. For the irradiation, this was also used to wire bond similar pads together, so that all five mini SSDs could be biased easily and at one time while being irradiated.

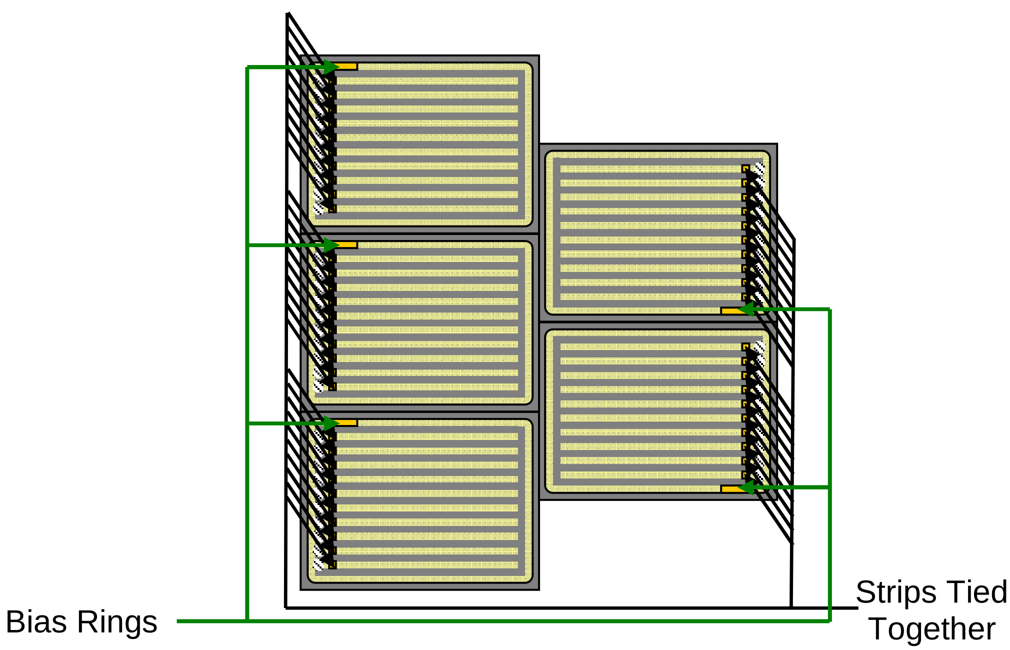

Figure 2.7: Irradiation Group Setup.

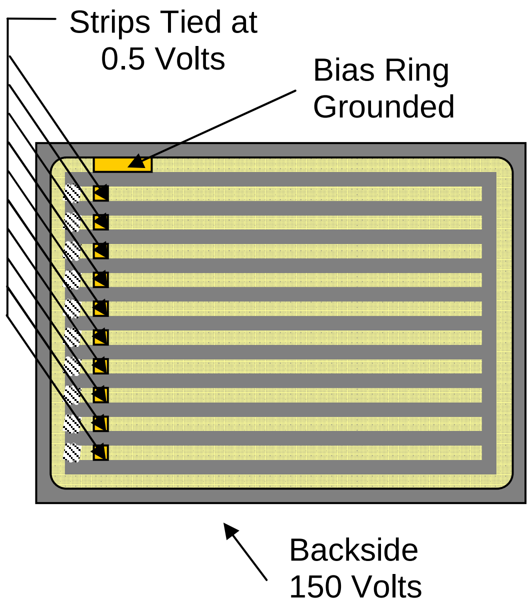

Figure 2.8: First Irradiation –
Biased and Strips on Voltage

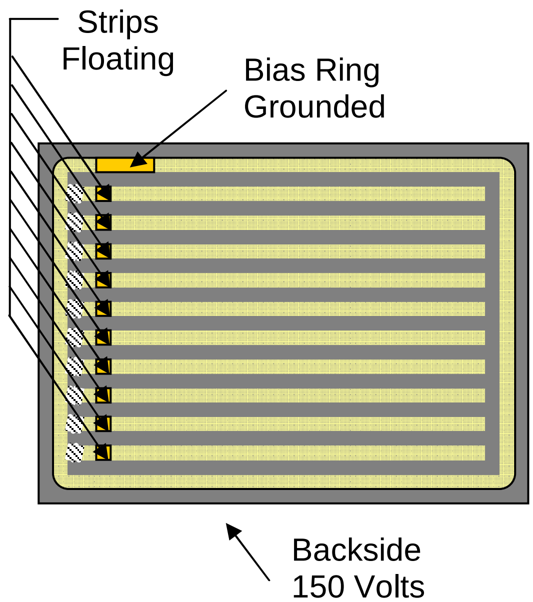

Figure 2.9: Second Irradiation –
Unbiased and Strips Floating

Post Irradiation Results

Current-Voltage Results, Biased Irradiation

Post irradiation results were not as straightforward. On June 24, 2008, the first set of mini SSDs was tested after the 1 Mrad irradiation at BNL. These mini SSDs were testing with strips both floating and grounded. The following graphs outline the breakdown voltages as a function of time. Tests conducted on May 11, 2008 were conducted just before irradiation, but after the strips were bonded out. Tests conducted on June 24, 2008 were the first tests after the mini SSDs had been returned. While there were a few exceptions, grounding the strips seemed to have little to no effect on the results of the I-V measurements. Between measurements the mini SSD were stored in a freezer to prevent excessive annealing. All tests here were done at room temperature.

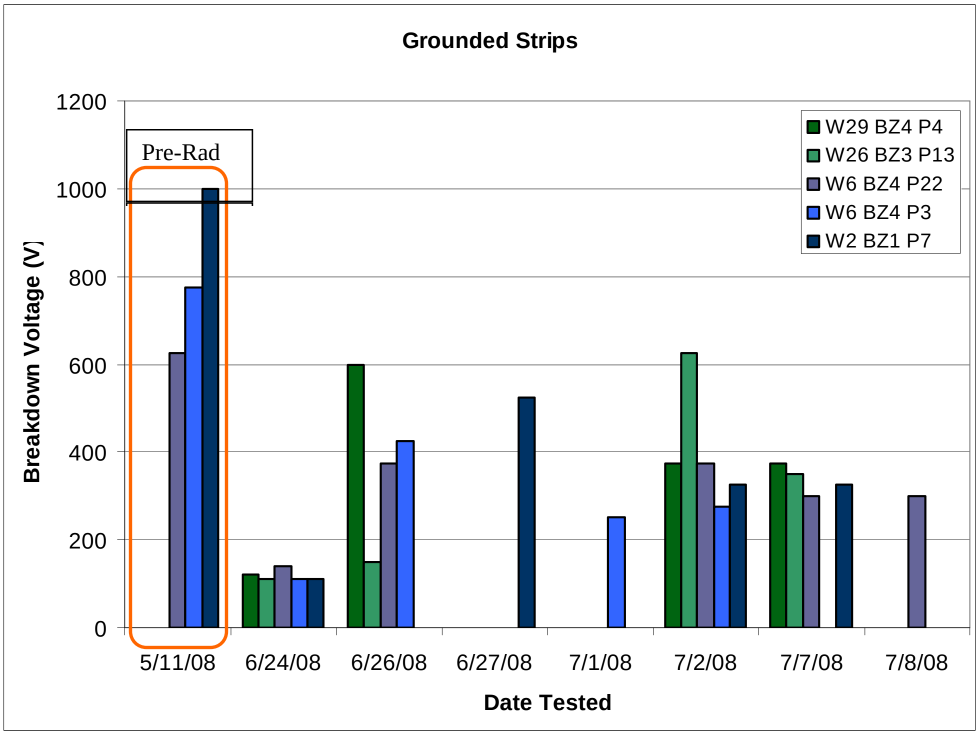

Figure 2.10: First Biased Irradiation I-V Summary (Grounded Strips).

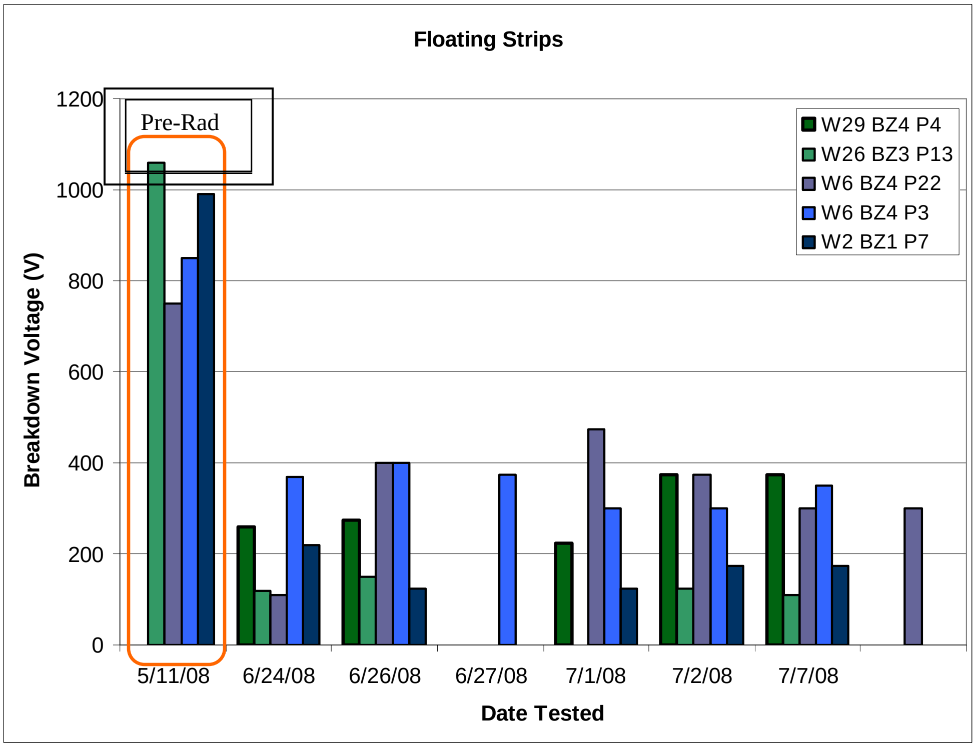

Figure 2.11: First Biased Irradiation I-V Summary (Floating Strips).

Various methods were used after the poor initial performance on 6/24/08 in order to recover the previous break down voltages from pre-irradiation, including cleaning of the surfaces using Nitrogen, as well as removing wire bonds which had become entangled. However, all mini SSDs showed a significant drop in breakdown voltage, which remained despite our efforts.

Current-Voltage Results, Un-biased Irradiation

After more questions were raised from testing the mini SSDs which were biased during gamma irradiation, a second batch was prepared and irradiated. This second batch was prepared the same way with all strips wire bonded out, but was not actually biased during the irradiation. Extreme care was taken with this set as well. It was believed that there may have been a time dependence over the days that the previous mini SSDs were tested, and as a result the second batch was tested in as close to one sitting as possible. The results are included below for two of the mini SSDs, while the third was irrevocably damaged before any useful results could be extracted.

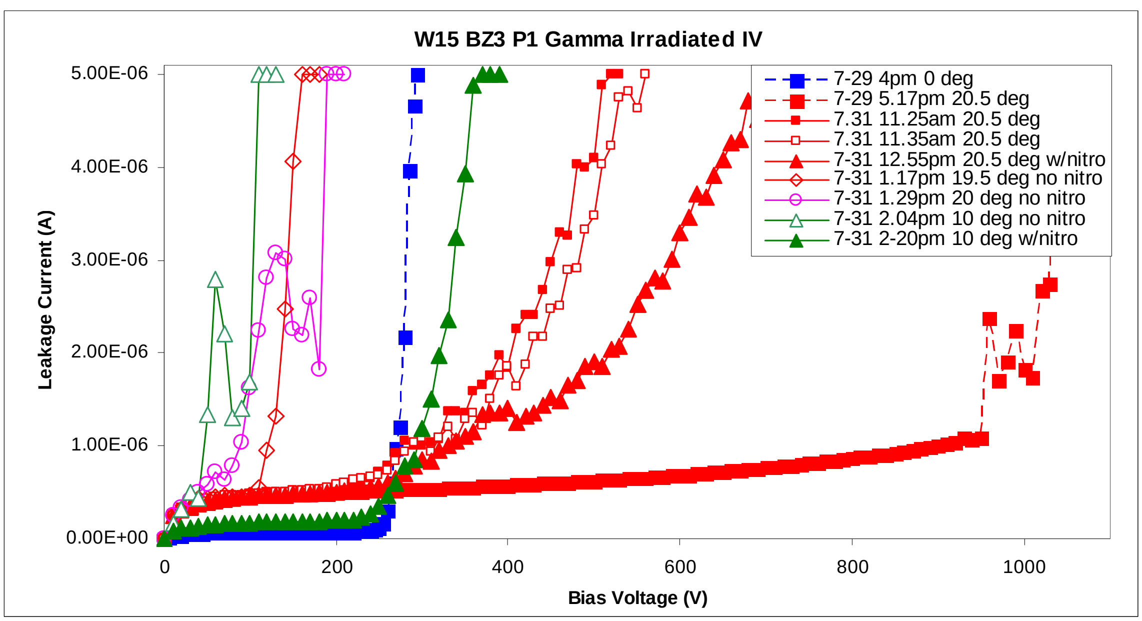

Figure 2.12: W15-BZ3-P1 Mini SSD I-V – floating strips.

W15-BZ3-P1 behaved abnormally at 0 degrees, possibly from cooling and moisture issues. The next tests allowed the mini SSD to warm back up, which resulted in a breakdown voltage very close to pre-rad. However, subsequent testing was not able to recover this result [Fig. 2.12]. Upon closer investigation surface damages were discovered [Fig. 2.13] after I-V testing was completed July 31, 2008.

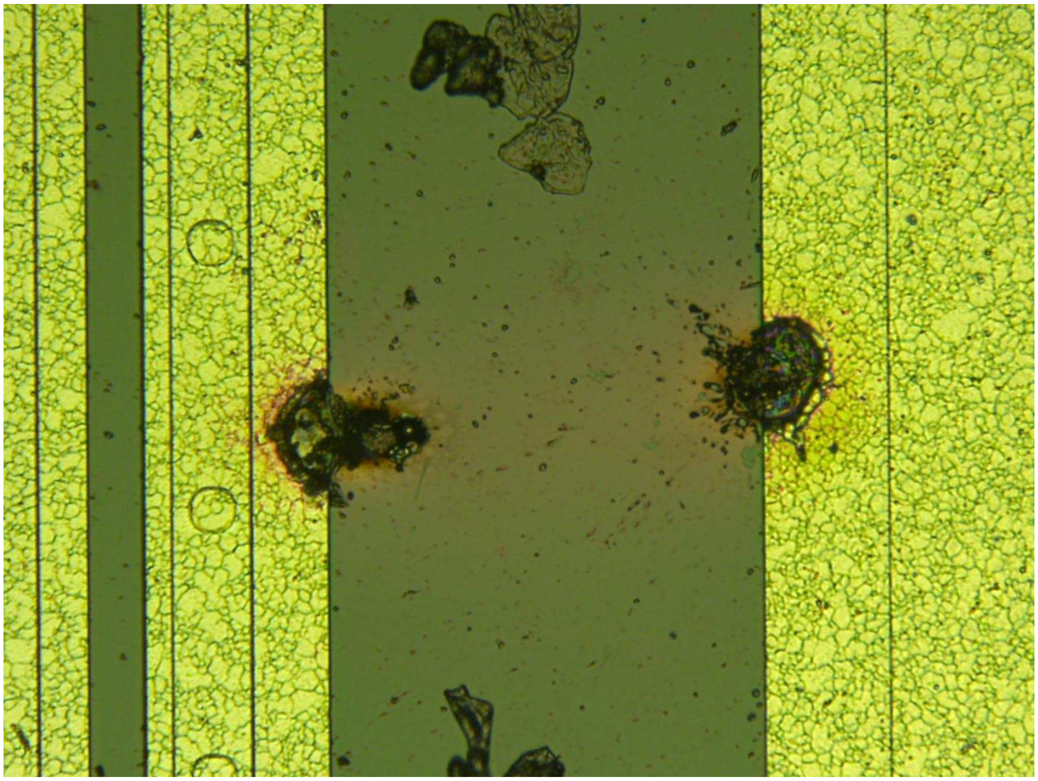

Figure 2.13: W15-BZ3-P1 discharge on guard ring and p+ implant.

The damage pictured here is between the high voltage metal ring which is electrically connected to the backside (right) and the guard ring (left)

.

The second mini SSD in this group was W16-BZ1-P7. A detailed list of I-V measurements is included in the graph below [Fig. 2.14]. The legend is ordered by date taken, with dashed lines being tests done on a different day. Also, colored lines are tests conducted with Nitrogen flowing, and the filled in symbols color signify the temperature which was maintained during testing. This graph is broken down into several time ordered steps to accompany an explanation of the testing procedure.

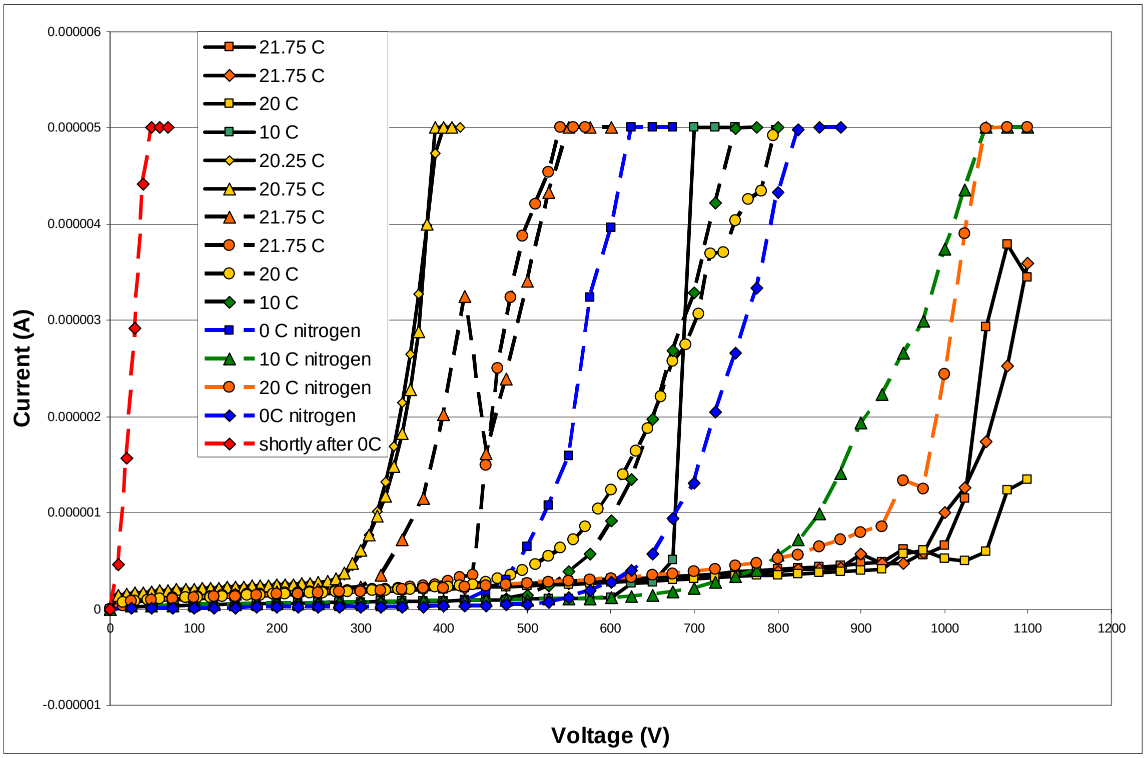

Figure 2.14: W16-BZ1-P7, unbiased irradiation I-V testing.

The mini SSD initially showed good performance post-irradiation. Two room temperature tests without cooling or nitrogen showed ~1,000 volt breakdown. This held true when cooling was used to bring the mini SSD down to an even 20 degrees Celsius. Next, the mini SSD was cooled down to 10 degrees Celsius, and the breakdown voltage decreased to 700 volts without any changes to the probe station since the previous test.

In an attempt to recover previous performance the mini SSD was brought back above 20 degrees Celsius, however breakdown continued to lower to ~300 volts without explanation [Fig. 2.15].

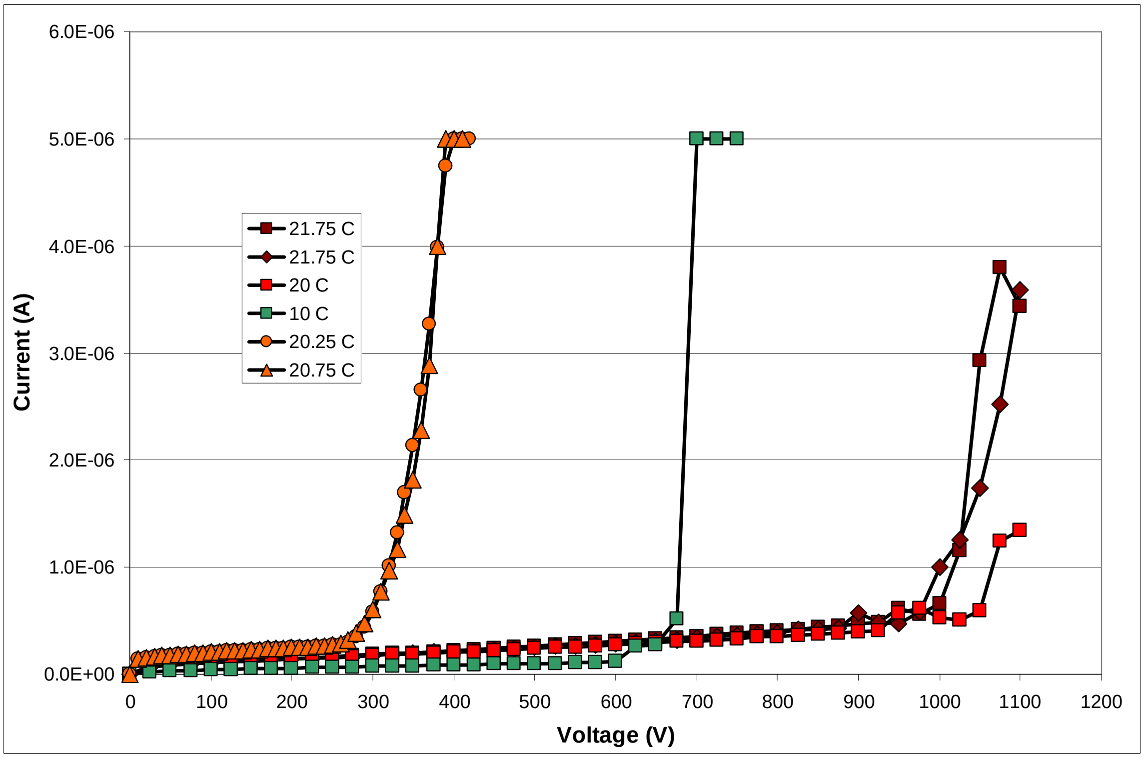

Figure 2.15: W16-BZ1-P7, unbiased irradiation I-V testing w/o nitrogen.

The mini SSD was removed from the probe station and placed in cooling to be tested on another day in an attempt to determine if the mini SSD would recover to previous breakdown voltages given enough time. These results show that as cooling was used the mini SSD increased to 500-600 volts breakdown, until 0 degrees was achieved and nitrogen was used. It is believed that not enough nitrogen was present to prevent some condensation forming on the mini SSD at this point, as the breakdown voltage decreased by 100 volts [Fig. 2.16].

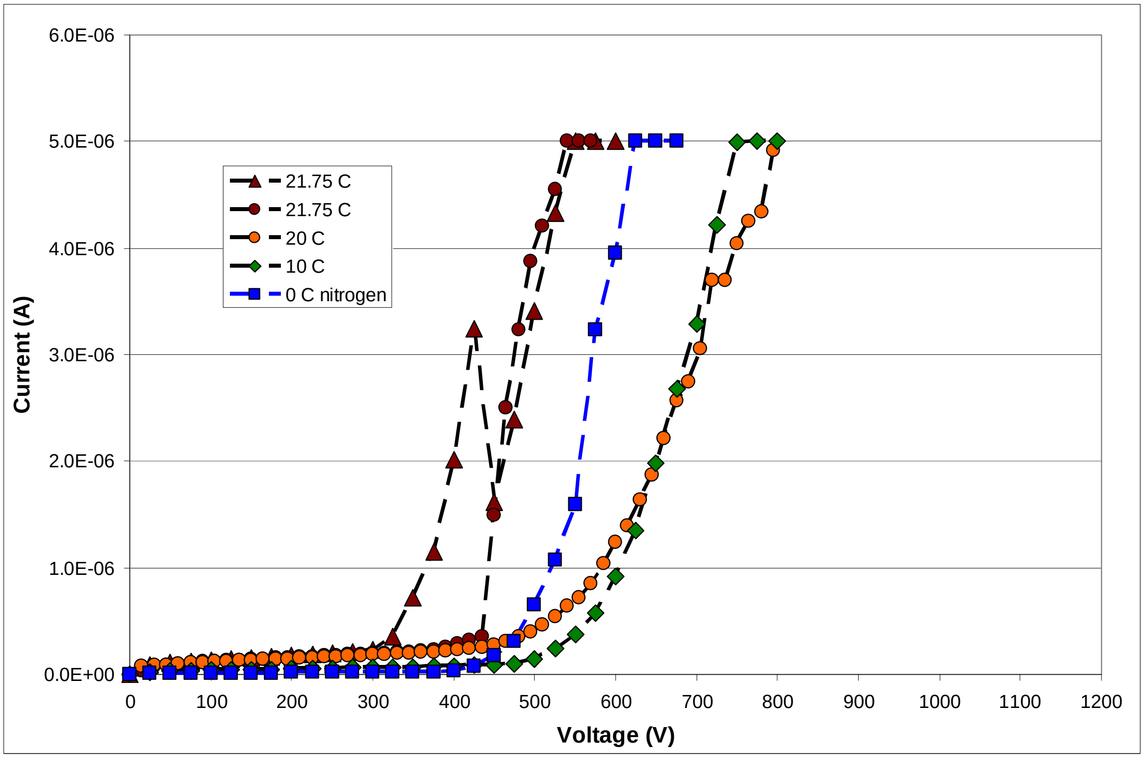

Figure 2.16: W16-BZ1-P7, unbiased irradiation I-V testing, follow up.

Near pre-irradiation breakdown levels were achieved by warming the mini SSD back up to 10 and 20 degrees while maintaining nitrogen flow. This was again reduced by 200 volts when taken down to 0 degrees again, possibly because the nitrogen flow was not sufficient. In addition to this decrease, tests immediately following this result showed the mini SSD to be irrevocably broken [Fig. 2.17]. It is important to note that throughout graphs 7 and 8 the testing setup was not disturbed as temperature and nitrogen control is handled remotely.

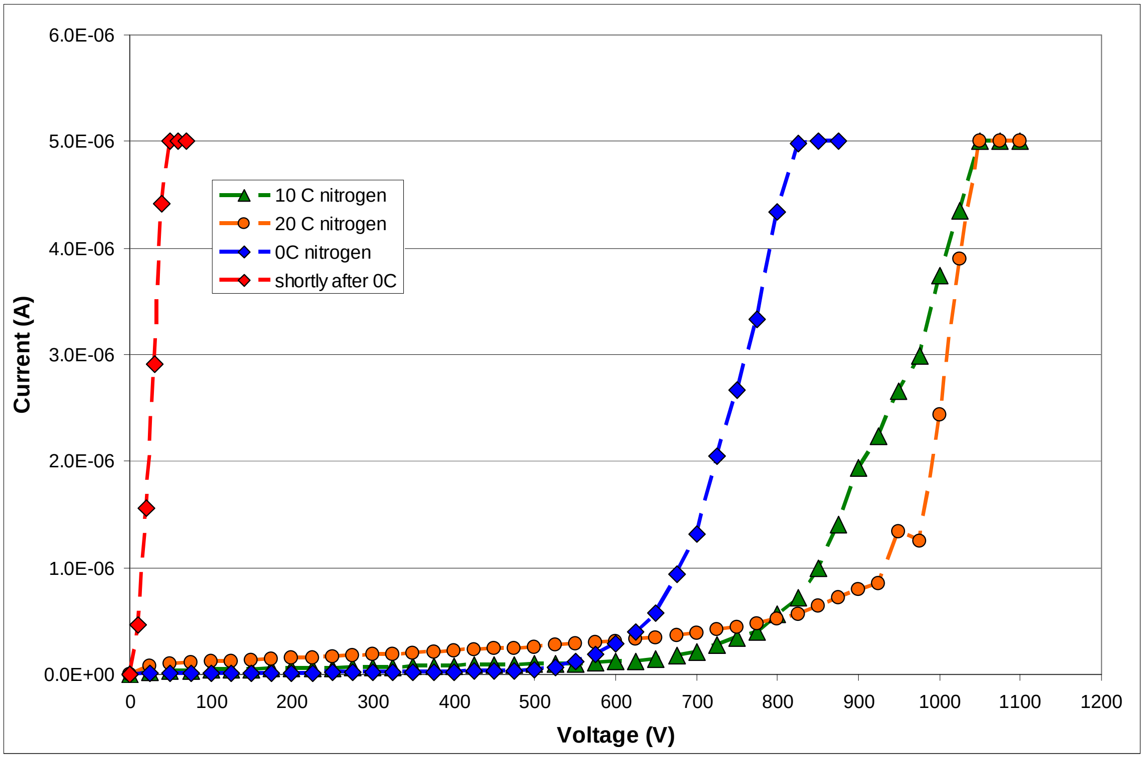

Figure 2.17: W16-BZ1-P7, unbiased irradiation I-V testing, follow up with nitrogen.

Immediately following this breakdown and linear I-V result the mini SSD was removed from testing for a visual inspection. While previous visual inspections had not discovered any obvious signs of damage, this inspection discovered damage on the mini SSDs surface [Fig. 2.18].

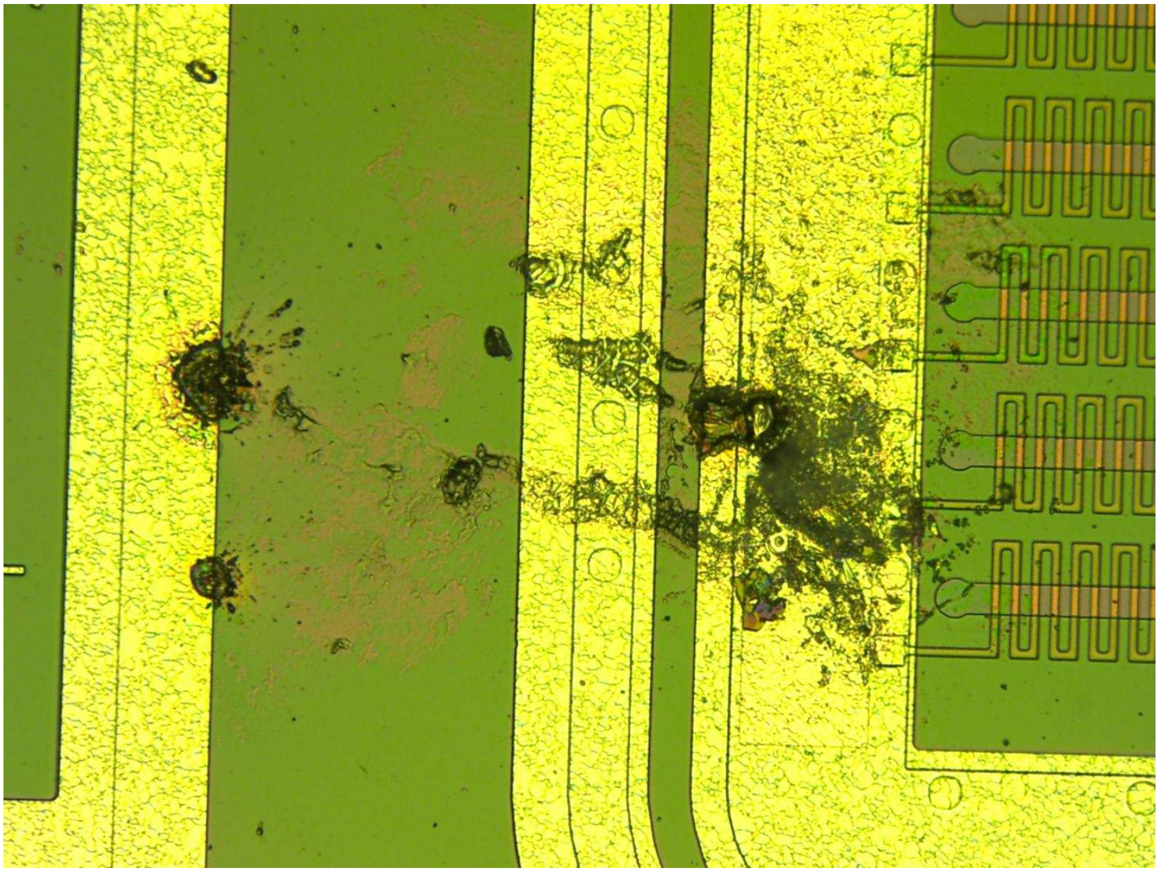

Figure 2.18: W16-BZ1-P7 bias ring pad damage.

This picture shows W16-BZ1-P7, and is focused on the edge of the mini SSD. The yellow strip to the left with the damage is electrically connected to the backside of the mini SSDs high voltage. The middle ring is a guard ring, which buffers the bias ring from the high voltage on the left. To the right is the bias ring which is grounded during testing, as well as the resistors which lead to the strips. One large and one smaller scorch mark can be seen bridging the high voltage ring and p+ implant before the guard ring. There is also a corresponding scorch on the edge of the bias ring. Attempts to remove some of the material obstructing the surface were not successful.

Post-Irradiation Capacitance-Voltage Results

Complete results for the post-irradiation mini SSDs for C-V are not available due to the increased time and effort in characterizing mini SSDs this way, combined with the mini SSD failures after I-V testing. However, a working C-V was obtained on mini SSD W06-BZ3-P3, and should be characteristic of the other mini SSDs. An I-V test is associated with each C-V, and is included in order to determine where the mini SSD breaks down.

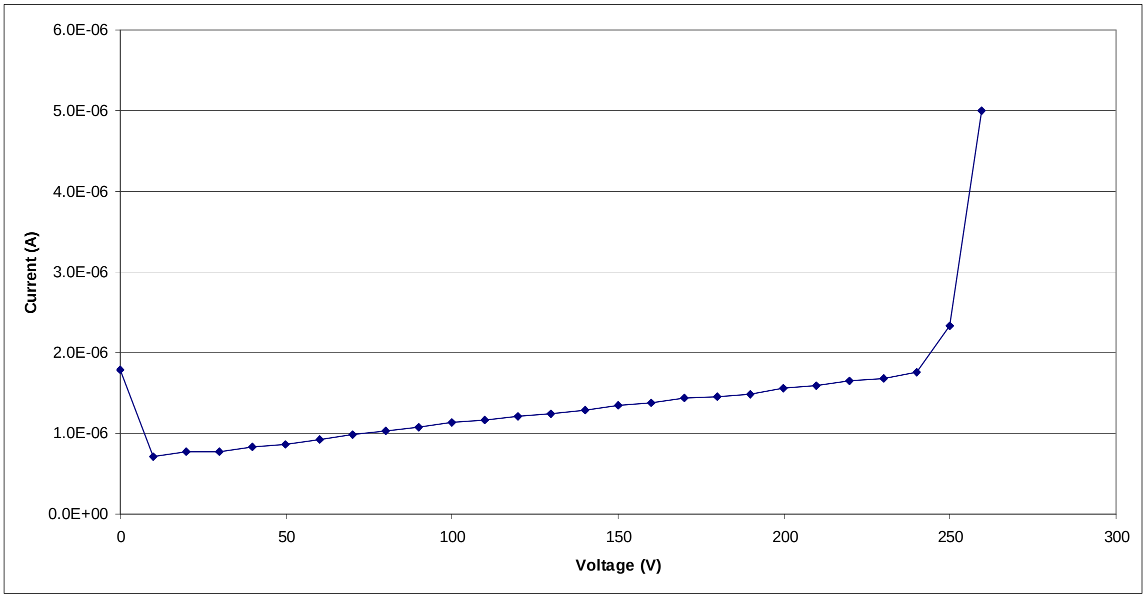

Figure 2.19: I-V associated with C-V for W06-BZ3-P3.

The I-V clearly shows breakdown above 250 volts [Fig. 2.19], which corresponds to the erratic behavior of the $1/C^2$ measurement above 250 volts. Alternatively, it can be seen that the turnover voltage has decreased from the pre-radiation value of 150, to roughly 120 volts [Fig. 2.20].

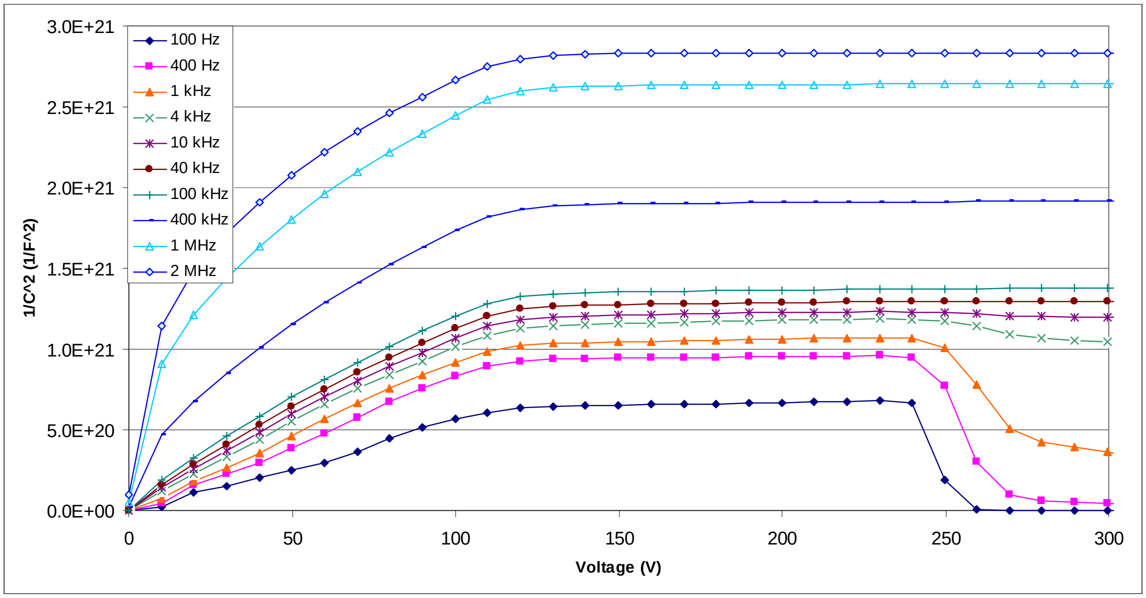

Figure 2.20: $1/C^2$ - W06-BZ3-P3.

Strip Testing

Furthering our investigation into the breakdown of these mini SSDs, we began to look at individual strips. To do this, we used the same setup as a normal I-V and changed voltage as we recorded the current at each step. In order to test individual strips the bonds to all strips were removed and a Keithley electrometer was used. We connected the electrometers high voltage probe to a single strips DC pad and grounded the low voltage probe. This effectively measured the voltage difference between the strips and ground, which when combined with the known resistance of the connecting 1.3 mega-ohm resistor, allowed us to calculate the current passing through that individual strip.

Below are the simple I-V results that went along with this test.

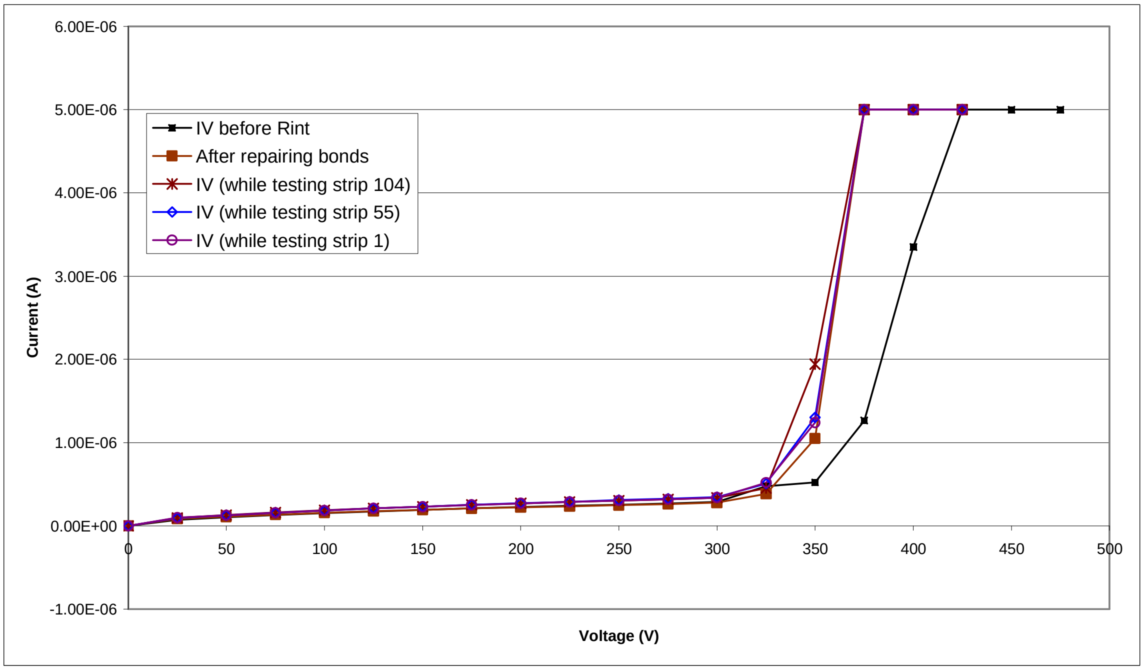

Figure 2.21: W29-BZ4-P4 I-V During Strip Testing.

These I-V curves showed no real changes, and did not reveal any strip specific breakdown. While the general breakdown voltage did decrease slightly between repairing some damage to the bonds, each individual strip tests I-V broke down at the same voltage. This contrasts with the data collected from the electrometer, shown below in Fig. 2.22.

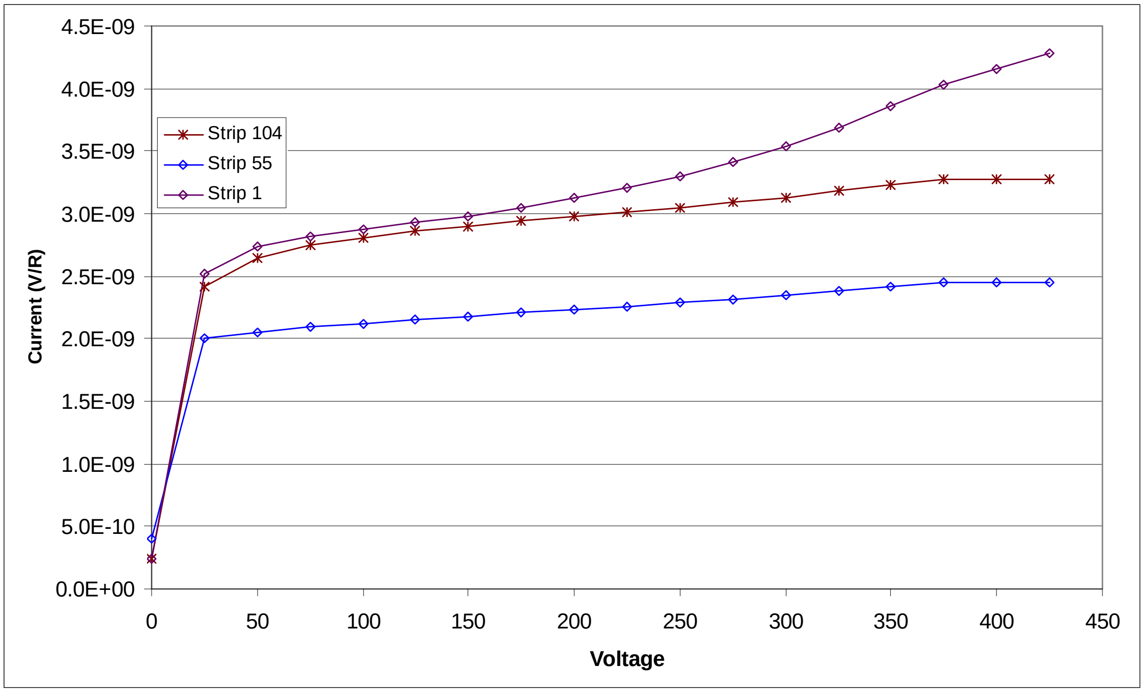

Figure 2.22: W29-BZ4-P4 Strip Current.

The strips are numbered from one side of the mini SSD, starting at 1 and ending with 104. Strip 55 was chosen for its proximity to the center, and lack of visible damage or debris. There was some slight visible damage near strip 1 on the guard ring. Overall, the outer strips showed 30% more current than the innermost strip, showing an uneven distribution of current through the strips, as well as an increase in leakage current with closer proximity to surface defects. The fact that the strips continued to show mostly stable current after the mini SSD itself had passed breakdown voltage shows that the strips are not breaking down in these tests.

A direct comparison shows the scale of this difference better. Here, the preceding two graphs are combined to show the difference in scale and rate of change [Fig. 2.23]. The strip currents were multiplied by 104 in order to scale them to the whole detector leakage current.

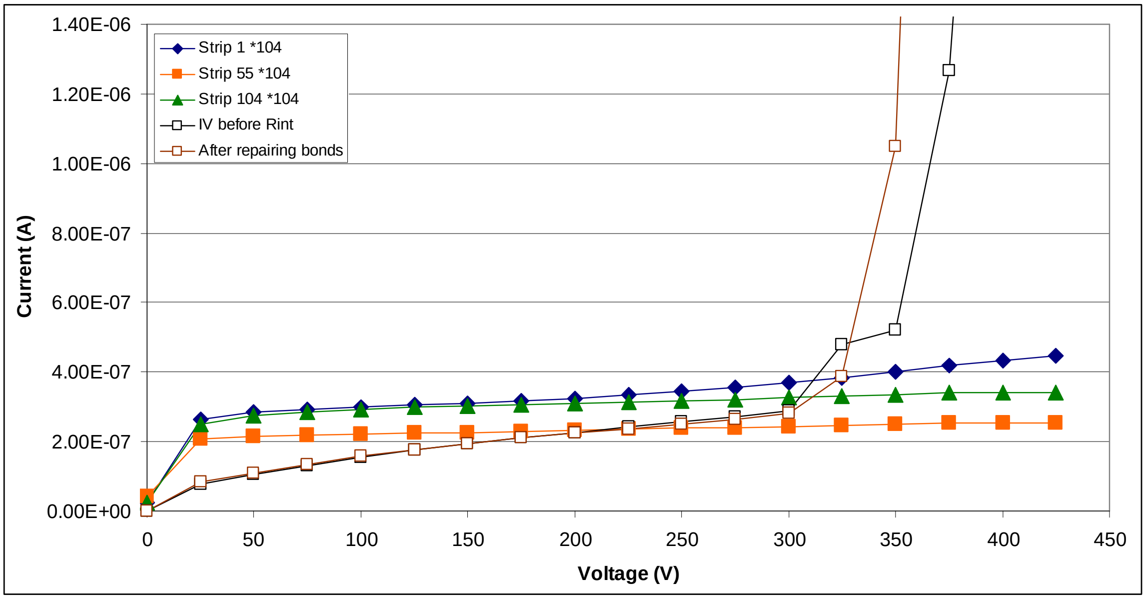

Figure 2.23: W29-BZ4-P4 Strip/Bias Current Comparison.

At 200 volts the overall strip leakage current is roughly 0.25 micro-Amps. At the same voltage, the current passing through the strips varies between 2 nano-Amps and 3 nano-Amps. Assuming a linear current profile across the strips, this averages out to roughly 0.25 nano-Amps across 104 strips, or roughly 0.25 micro-Amps. Here the strip current is of the same order as the entire mini SSDs leakage current.

At 400 volts the innermost strip has roughly 2.5 nano-Amps passing through it, and the two outer strips have a little more than 3 to 4 nano-Amps each. Again, averaging these values and multiplying by 100, we have a current on the order of 300-400 nano-Amps. However, the entire mini SSD current at this point is far higher at 5 micro-Amps. This order-of-magnitude difference shows that as the mini SSD breaks down there is an excess current which is bypassing the strips and travelling between the bias and guard rings, eventually leading to a surface discharge and overall mini SSD failure.

3. Discussion

All mini SSDs tested showed a significant drop in breakdown voltage following irradiation. Initial tests showed little to no change. However, over time this breakdown performance decreased. Use of Nitrogen was able to mitigate this in one case. All mini SSDs had breakdown near or above 800 volts pre-rad, and typically had breakdown at or below 400 volts by the end of the testing.

Surface discharges and other effects were seen on a variety of these mini SSDs, which leads us to believe that breakdown occurred on the surface of these mini SSDs. Further investigation through strip testing revealed the most likely cause of these surface breakdowns between the bias and guard ring. As the mini SSDs broke down, the strips stayed at relatively the same voltage/current. This could mean that the excess current travelled through the bias ring directly to the guard rings. This large potential difference would cause the mini SSD to physically breakdown between the bias and guard rings, resulting in electrical arcing discharges. Another possibility is that the passivation provided an open path for current to travel combined with surface charges which could have gathered on the mini SSDs p+ implant between the bias ring and high voltage.

Many of these mini SSDs were inspected several times throughout our testing process. Following large shifts in their breakdown voltage, inspections often revealed what appeared to be the visual evidence of the mini SSDs breakdown. Several of these pictures are included below.

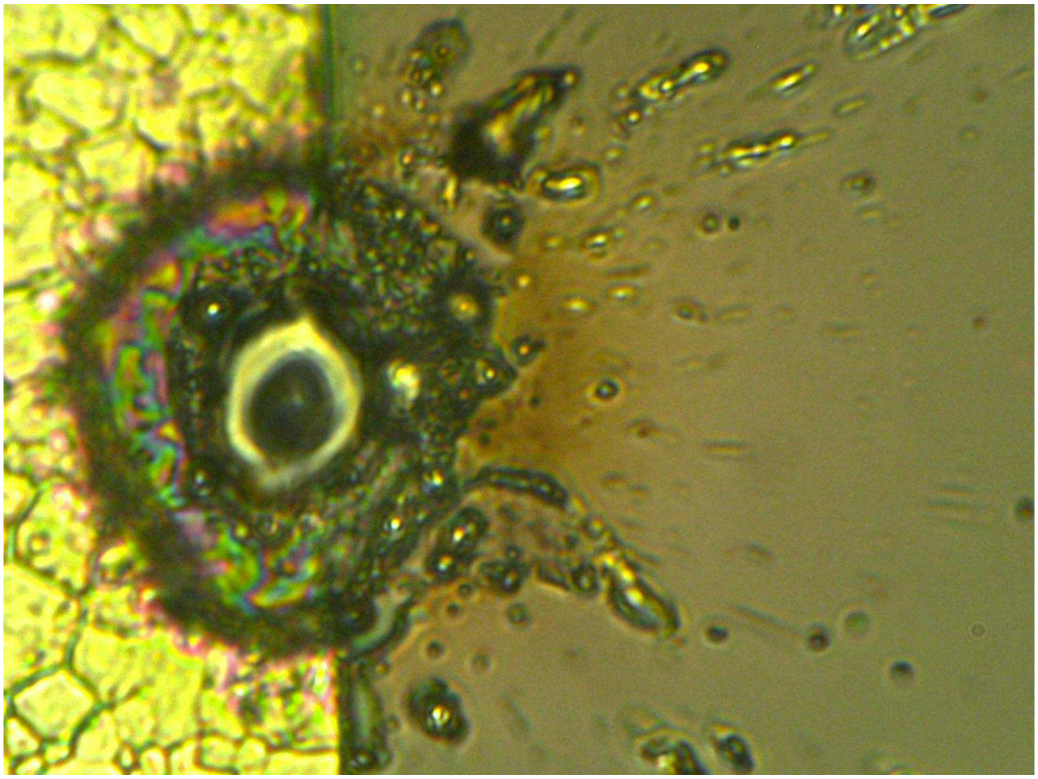

Figure 3.1: W6-BZ3-P3 P+ crater zoom (biased irradiation, grounded strips).

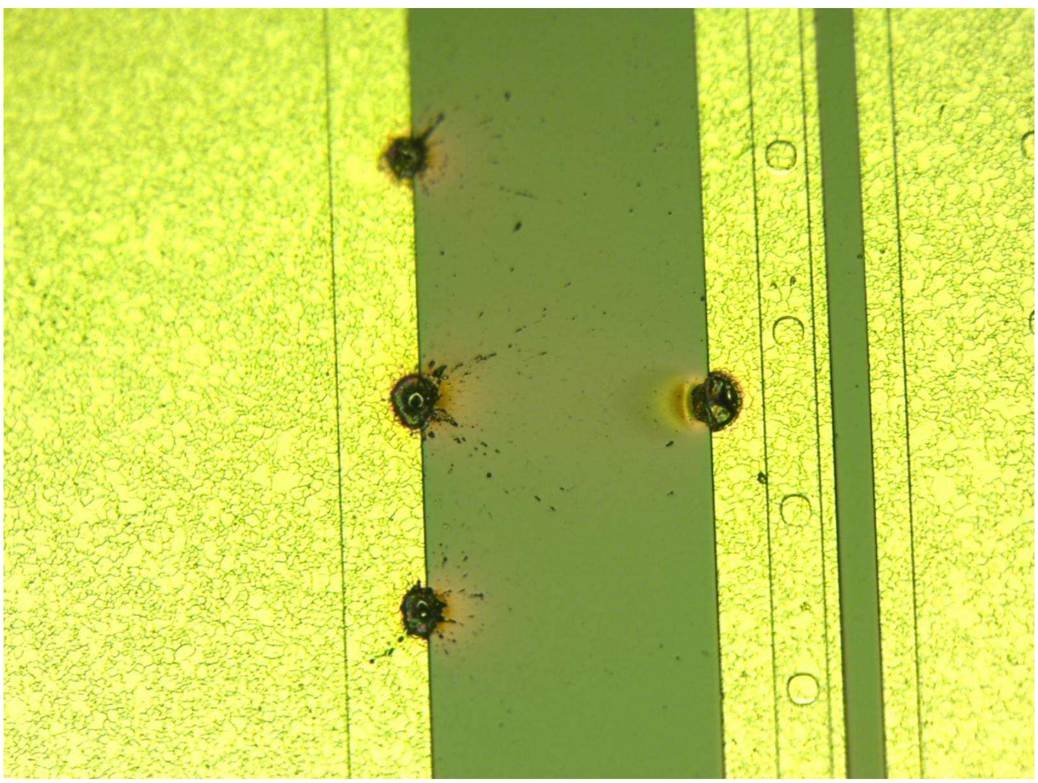

Figure 3.2: W6-BZ3-P3 guard ring and p+ implant damage(biased irr., grounded strips).

4. Conclusion

The I-V results from these mini SSDs post irradiation showed significant and generally catastrophic failures, resulting in a second irradiation for further investigations. Further testing showed that careful testing along with a dry air (Nitrogen) environment allowed almost full recovery of pre-radiation breakdown voltages in at least one case (W16-BZ1-P7). Visual inspections of these mini SSDs verified that significant electrical discharges occurred on the surface of the mini SSDs. These discharges occurred most frequently between the guard ring and P+ implants running around the mini SSD on the surface. These two areas carry a high potential difference, and it is possible that the irradiation decreased the mini SSDs passification and resistance, or that charges were allowed to build up in this area. Tests conducted on mini SSDs with this damage showed linear I-V curves, implying a resistance characteristic of roughly 10 mega-ohms. Mini SSDs with only minor damage may have had reduced resistance which lead to increased currents, and eventually a surface discharge which resulted in a short on the mini SSD.

Several lessons were learned from these experiments. The most important of which is to always conduct visual inspections before and after tests in order to better determine precisely when detectors become damaged. Secondly, grounds must always be observed in order to avoid any possible accidental user-induced discharges. Finally, it may be necessary to investigate alternative touchdown methods where the probe is disconnected from ground and left floating while touching down in order to prevent any possible charge buildup on the detector from discharging to the detectors surface. However, many of the discharges witnessed happened mid-test and away from probe tips. Their exact cause remains undetermined.

5. Works Cited

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