Voltages on Silicon Microstrip Detectors in High Radiation Fields

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Abstract

The voltage between the AC-coupled readout strips and the silicon strip implants on a silicon microstrip detector in a high radiation field was investigated. The ionizing radiation was supplied by infrared lasers of varying intensity, creating ionization patterns that mimic those created by a flux of minimum ionizing particles. At high laser intensities, a complete breakdown of the operational electric field within the detector was achieved and studied as a function of laser intensity and connected circuit components. It was discovered that for a single-sided silicon microstrip detector, with n-type bulk, n-type silicon implant strips, and a p-type backplane, the voltage difference between the readout strips and the silicon implants could be minimized by using a large resistor between the backplane and the bias supply, and a small capacitor between the backplane and ground.

I. Introduction

In the last 10 years, silicon microstrip detectors have increasingly been used as vertex detectors in high energy physics experimentation. Due to the proximity to the interaction region in colliding experiments, these detectors are subject to damage when beam losses occur. At low repetition rate colliders, like LEP, the experiments are protected from beam losses by early detection and beam abort systems. However, there are still reports that detectors at LEP have been damaged by large beam losses [1]. This failure is explained as a result of the large ionization created inside the silicon detectors. The electric field which biases the detector collapses, and the two detector sides float to an unknown voltage, creating possibly large voltage differences between the silicon implants and the aluminum readout strips. The advent of high luminosity colliders with short bunch spacing, like the B-Factories and the LHC, makes this protection system obsolete, and one has to face the possibility that the detectors will have to absorb the radiation due to beam losses. If the beam loss is expressed in terms of the total radiation dose absorbed by the silicon detectors, one Rad is equivalent to a flux of approximately $3{\times}10^7$ minimum ionizing particles per cm^2 [$\mathrm{MIP/cm}^2$] impinging on a detector of 300μm thickness. As the detectors are designed to detect single MIPs, each of which generates 1fC = 24,000 electron-hole pairs in 300μm thick wafers, absorbing the beam loss of one Rad is clearly outside the design criteria of the silicon detectors. This motivates us to investigate systematically the consequences of an event where a large number of charges are created in the silicon bulk.

In previous publications, we have shown that signals from MIPs can be simulated in silicon detectors by infrared (IR) laser light [2] because the absorption length of IR light is on the order of millimeters in silicon. We use the same method here, but increase the intensity of the laser so that the absorbed dose affects the operating electric field inside the detector.

II. Theory of $\vec{E}$-field Breakdown

Under normal operation, the silicon detector is biased so as to create a depletion region within the silicon bulk (reverse biasing). This voltage difference, on the order of 100V, sets up surface charge densities on the implants and the backplane, and there is a net positive charge within the silicon bulk for the typical n-type material. Charge is also stored on any capacitors in series between the detector and ground. Overall charge neutrality is maintained, and an electric field is maintained between the implants and the backplane.

When the detector is subjected to a high radiation field (i.e. a heavily ionizing particle or a large flux of lightly ionizing particles), the deposited energy within the silicon bulk creates a large number of electron-hole pairs. Because of the large number of free charge carriers, the detector is no longer able to sustain a voltage difference between the implants and the backplane, and current flows freely through the detector until the free charge carriers have been cleared from the bulk. During the breakdown period, the implants and the backplane have the same voltage, which is determined by the external components of the detector circuit.

A simple diagram of the silicon microstrip detector with external electrical connections is shown in Figure 1. In trying to determine the voltage at which the detector floats after severe irradiation, one can make a first guess by assuming that the value of the resistor connected in series to the backplane is large enough to prevent significant current flow during the breakdown. The voltage during breakdown is then determined by the surface charges on the implants and backplane, and by the charge stored on the capacitor (C) between the backplane and ground. Since current flows through the detector as the free charge carriers are being cleared, another voltage is determined by the ratio of the backplane resistor (R) to the resistors tying the implants to ground[1]. The voltage to which the detector floats during the breakdown period should be able to be controlled, therefore, by an appropriate choice of resistors and capacitors connected to the backplane.

III. Experimental Design

The silicon strip detectors used in our studies were ATLAS nn80 detectors of 300μm thickness [3]. These have 16μm wide n-type silicon implant strips on 80μm pitch n-type silicon

[1] In the detector used for these tests, a 1MΩ resistor connected each individual silicon implant to ground. However, the breakdown region encompasses many implants, and so some combination of resistors in parallel must be used in determining the floating voltage of the detector.

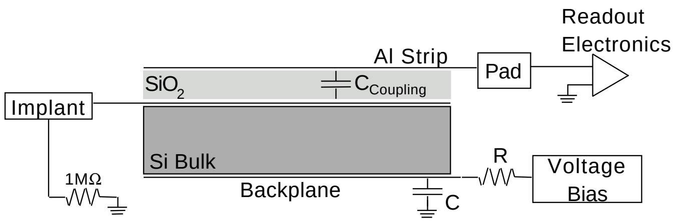

Figure 1: A simple model of the silicon strip detector (side view) with significant electrical connections

bulk. The Al readout strips are AC-coupled to the implants and connected to fast ATLAS electronics. Each implant is connected to a common ground via a 1MΩ polysilicon resistor. The negative voltage bias is supplied to the p-type backplane via a resistor-capacitor network (the significant portion is shown in Figure 1.) The voltage on the strips and backplane was determined by the use of either a pico-probe or a simple steel probe.

Two different lasers supplied the IR light of wavelength 1064nm. The time structure of the lasers was determined with a photo-multiplier tube. For lower intensities, we used the BNC H1064 signal laser, which allows changing the intensity continuously up to 50mW and the length of the laser pulse in four steps from 2ns to 10ns. For larger intensities, we used an Alessi probe-station cutting laser. The output of the cutting laser consists of a number of short "spikes" of 1μs duration and equal intensity. Increasing the laser power increases the number of these short pulses. The power setting "510" corresponds to three laser spikes, while the setting "530" corresponds to roughly twelve spikes. The number of spikes and the length of the pulse train increase approximately linearly with the instrument power setting.

IV. Deposited Energy at Different Laser Intensities

The relationship between laser intensity and deposited energy was determined experimentally using the detector with the Al readout strips unconnected. This was done by measuring the voltage pulse on an implant, and integrating it in a digital oscilloscope. The total charge is then the integral of the current, which can be calculated using the known value for the bias resistor of 1MΩ:

$$Q = \frac{\int V\,dt}{R} = \frac{\int V\,dt}{10^6} \tag{1}$$

Using the BNC laser, the ionization is confined to a few strips, as shown in Figure 2.

Although the main pulse is very short (≈50ns), a long tail is observed and the pulse integral is evaluated in a 10μs window. The relationship between laser intensity and observed peak height of the voltage signal on the implants is shown in Figure 3, and the integral of the response pulse including the very long tails up to 10μs in Figure 4, respectively, both for different laser width. Both relationships are approximately linear.

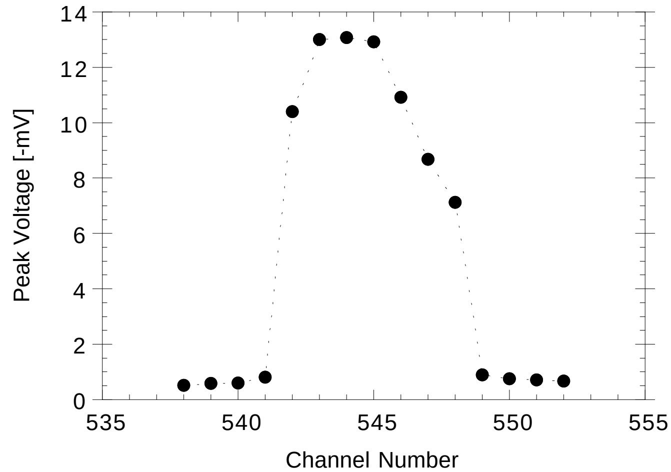

Figure 2: Peak voltage on neighboring strips with BNC laser set at width 4 and 50mW power (floating Al strips)

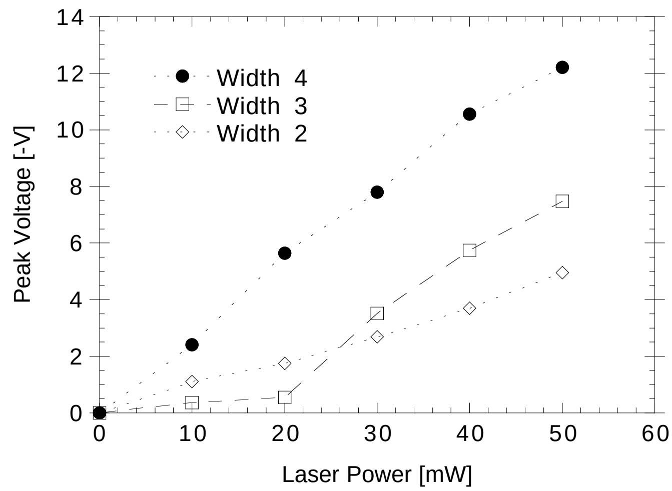

Figure 3: Peak voltage on implant as a function of BNC laser width and power setting (floating Al strips)

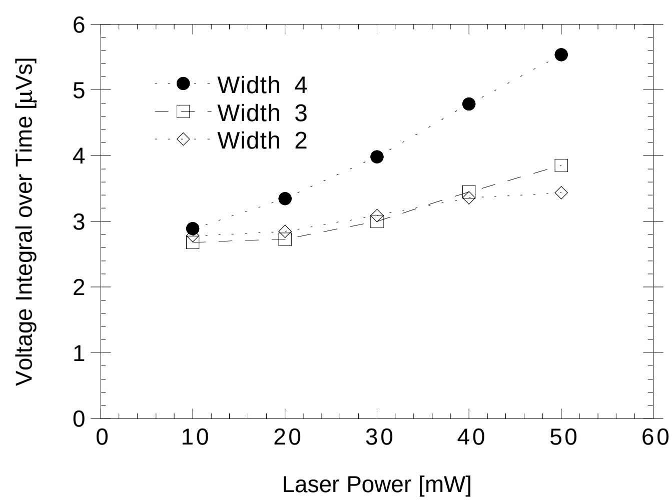

Figure 4: Voltage integral observed in 10μs on silicon implant as a function of BNC laser width and power setting (floating Al strips)

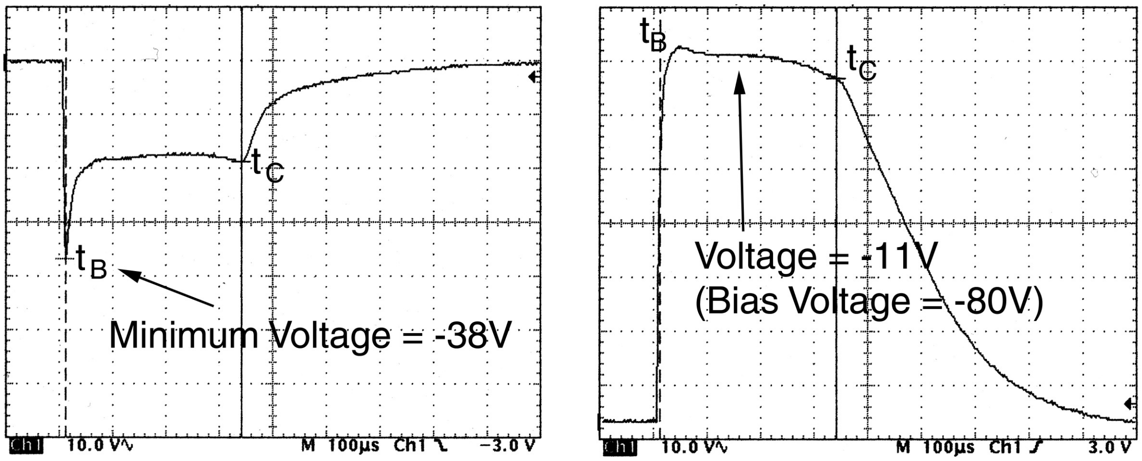

Figure 5: The plot on the left indicates the voltage versus time of the implant, and the plot on the right indicates the voltage on the backplane. They meet at the same voltage during the breakdown. For these plots, $R = 9\mathrm{k}\Omega$ and $C = 9.4\mathrm{nF}$. The bias voltage on the backplane is -80V.

The voltage integral for the laser pulse of width 4 and 50mW power is 5.5μVs, which by Equation 1 gives a total free charge of 5.5pC, or 1.4×10^3 MIPs. Thus, we find that a signal of approximately 1,400 MIPs on one strip yields a peak voltage of about -12V.

V. Characteristics of Radiation Induced $\vec{E}$-field Breakdown

For the cutting laser, a total breakdown of the electric field inside the detector was achieved. For these experiments, the Al readout strips were bonded to the amplification circuitry, keeping them tied to a virtual ground (see Fig. 1). While free charges remain in the silicon bulk, the implants and the backplane float to the same voltage, and current flows through the detector. The typical voltages on the implants and on the backplane during a breakdown as a function of time are shown in Figure 5. The curves can be broken into three different time periods: the initial electric field breakdown, the clearing of free charge carriers, and the return of the normal electric field within the silicon bulk. In particular, let t_B denote the time at which the implants and the backplane come to the same voltage (the electric field has broken-down) and let t_C denote the time at which all of the free charge carriers have been cleared. Though there is some variation with different resistor and capacitor values, t_B is generally between 5μs and 10μs. The clearing time is strongly dependent on the resistor connected to the backplane, between 100μs and 1ms.

The laser beam used has a diameter of only about 10μm, but the ionization within the detector and the breakdown of the electric field has a greater range. Tests were conducted to demonstrate the behavior of the detector at regions far from the laser. Figure 6 demonstrates the voltage integral over time on the silicon implants as a function of distance. As with the BNC laser, we assume that the voltage integral is proportional to the total ionization in the immediate vicinity of an implant strip. The voltage integral begins to decrease at a distance of about $\pm$1.6mm, and the ionization is almost nothing at a distance of about $\pm$10mm[2]. The character of the voltage breakdown within $\pm$3.2mm is as described above, where there is a complete breakdown of the electric field within the silicon detector. At further distances, the voltage spike is more characteristic of the signals recorded by the BNC laser that do not result in a complete breakdown of the electric field.

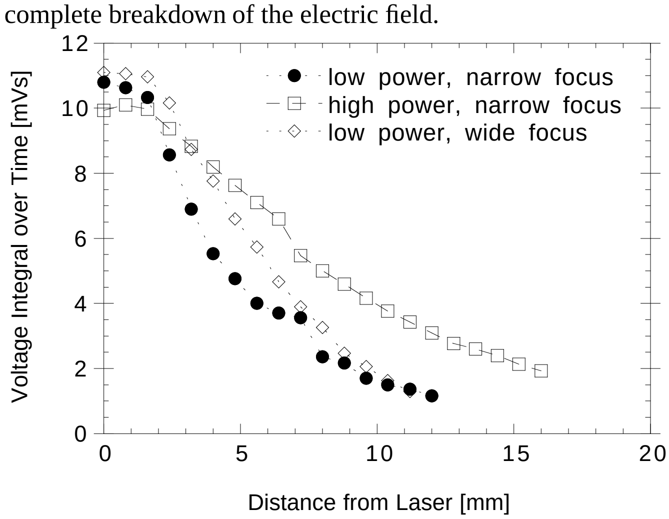

Figure 6: Voltage integral over time on the silicon implants as a function of distance from the laser. Two different power settings and two different magnifications were used to determine what affected the spread of ionization within the silicon bulk.

It was found that the voltage to which the implants floated during the breakdown period was strongly dependent on the combination of resistors and capacitors between the backplane and the voltage source. With the detector arranged as in Figure 1, a trend was found relating (1) the capacitance C to the initial breakdown voltage peak (at time t_B) and (2) the resistance R to the voltage at the end of the clearing time (at time t_C). These trends are illustrated in Figures 7 and 8. In order to minimize the change in voltage on the implants (and maximize the change in voltage on the backplane,) one must

[2] These are linear distances perpendicular to the implant strips.

have a low capacitance and a large resistance connected to the backplane. Since the charge stored on the capacitor distributes itself in the detector after the electric field is removed, a large capacitance leads to a large spike at the beginning of the breakdown period at time t_B. While free charge carriers remain within the silicon bulk, current flows through the detector, and the voltage of the implants and backplane is determined by an effective voltage divider. The resistor on the backplane is half of the divider; the other half is the effective resistance of a certain number of implant resistances acting in parallel. Current flows freely through approximately 100 implants, and each implant is connected to ground via a 1MΩ resistor, so we expect the equivalent resistance to be approximately 10kΩ. Data show that the effective resistance was very close to this value for most configurations.

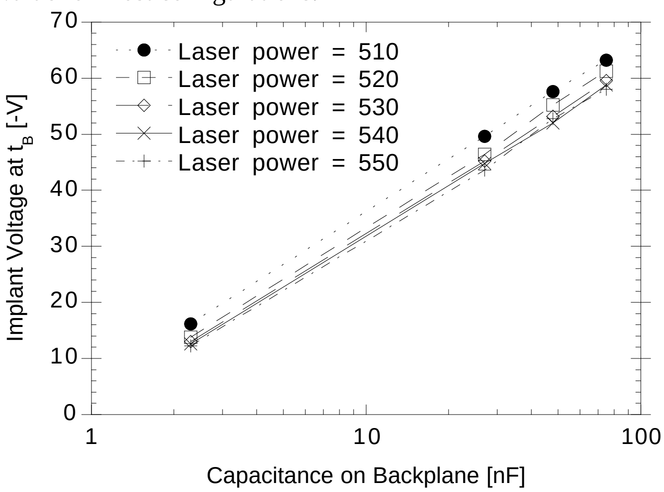

Figure 7: Implant voltage at the beginning of the breakdown period (time t_B) as a function of the backplane capacitance.

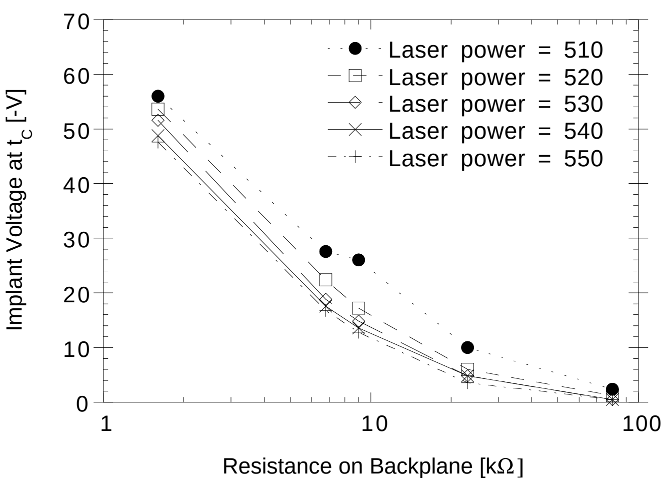

Figure 8: Implant voltage at the end of the clearing period (time t_C) as a function of the resistance on the backplane.

Since the motivation for this research is minimizing the voltage difference between the silicon implants and the Al readout strips (which remain at virtual ground), we plot the peak voltage on the implants as a function of both resistance and capacitance in Figure 9. When the resistance was 1kΩ, the shapes and the lengths of the recorded pulses were influenced by other capacitances in the circuit; this may explain why the peak voltage does not fall as quickly at low capacitances as the 9kΩ and the 150kΩ resistances, though no trends relating these other capacitances could be discerned.

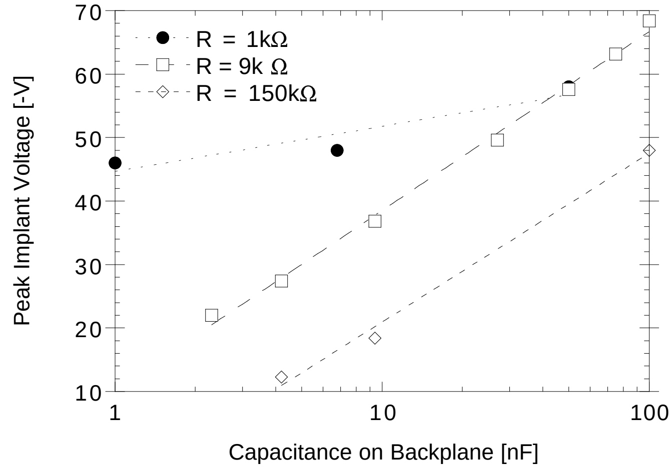

Figure 9: The peak voltage on the silicon implants during a breakdown as a function of the resistor and capacitor connected to the backplane.

VI. Anticipated Charges and Voltages in High Energy Physics Applications

The results from the preceding sections can be compared with anticipated experimental particle densities:

1. One Rad of total dose corresponding to 3×10^7 MIP/cm^2. A strip 6cm long and 80μm wide has an area of 0.05cm^2, and thus receives 1.5×10^6 MIP, which surely shorts out the detector [2].

2. ATLAS SCT with 12cm long strips, anticipated yearly fluence of 2×10^{13}/cm^2 (i.e. a flux of 2×10^6/cm^2/s). The number of MIPs passing through a single strip of 12cm length (i.e. 0.1 cm^2 area) during the collection time of 200ns established above is about 0.4, and the expected voltage offset of the implants is 3mV, if we scale the results with the BNC laser from above [4].

3. A GLAST relativistic Fe nucleus will generate a charge equivalent to 1000MIPs in the 400μm thick GLAST detectors. This is not enough charge to short out the detector. The voltage offset for such a charge was measured to be 8V on unbonded strips. In addition, the strips have a punch-through voltage of about 10V, which could mitigate the voltage build-up. Clearly a careful investigation of the filter network of the GLAST detectors is called for.

VII. Conclusions

High radiation fields can create enough ionization within silicon detectors to collapse the operating electric field, and a potentially large voltage difference can arise between the Al strips connected to readout electronics and the silicon strip implants. This voltage difference can potentially lead to failures in the operation of these detectors. We study the factors which influence the voltage to which the silicon implants float during a breakdown by using high intensity infrared lasers. The size of the region in the detector which experiences a total breakdown of the operating electric field is dependent on the intensity of the laser. Furthermore, we find that the voltage difference between the implants and the Al strips can be controlled by the choice of capacitance and resistance connected to the backplane. This voltage difference is relatively unaffected by the intensity of the laser when total breakdown occurs. The data indicate that if one wants to minimize the voltage across the coupling capacitance between the readout strips and the silicon implants (in this configuration), one should minimize the capacitance between the backplane and ground and maximize the resistance between the backplane and the voltage bias.

VIII. References

[1] ALEPH Detector: A. Litke, private communication

[2] S. Gadowski, et al. *Nuc. Inst. and Meth. in Phys. Research, Section A*, vol. 326, 1993 p. 239

[3] P. P. Allport, et al. *NIM A*, vol 386, 1997 p. 109

[4] W. Atwood *NIM A*, vol 342, 1994 p. 302