The Effect of Humidity on Reverse Breakdown in 3D Silicon Sensors

H. McDuff^a, M. Hoferkamp^a, S. Seidel^a, R. Wang^a, C. Kenney^b, J. Hasi^b,
S.I. Parker^c

^a*Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131*

^b*SLAC National Accelerator Laboratory, Menlo Park, CA 94025*

^c*Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, HI 96822*

February 6, 2015

Abstract

The effect of humidity on reverse breakdown in silicon sensors of the “3D” geometry is studied for unirradiated and irradiated samples exposed to fluences relevant to the environment of the High Luminosity Large Hadron Collider. Leakage currents are measured and breakdown voltages are compared for a range of relative humidities and bias voltages. The proton beam at LANSCE, Los Alamos National Laboratory, was used to irradiate samples with 800 MeV protons up to 2×10^{16} p/cm².

1 Introduction

3D silicon sensors [1, 2] have applications in a wide range of fields, but most notably they are planned for use in experiments at the Large Hadron Collider (LHC) because of their radiation hardness. A critical operating parameter of 3D sensors is breakdown voltage (V_{BD}). In this study we examine the effects of ambient humidity on 3D sensor breakdown by measuring leakage current and breakdown voltage as a function of relative humidity (RH) for constant temperature.

The environment in which 3D sensors will be used in LHC experiments such as ATLAS is well-controlled below 0°C with relative humidity effectively zero in a dry N₂ environment. Outside the controlled environment of the experiments, in beam tests and during planned and unplanned warm-ups, the effects of humidity upon the performance of the sensors must be anticipated. Additionally the humidity response of the sensors must be considered when developing plans for future cooling methods.

Studies have been made of the effect of humidity on capacitance [3, 4] and leakage current and breakdown [5, 6] in planar silicon strip sensors. However, data on humidity effects on 3D geometries are not readily available in the literature.

2 Method

2.1 Devices

The devices [7], manufactured at SLAC, are 3D sensors in n-type bulk with active edges [8]. Figure 1 shows their layout. Three signal electrodes are in each $50\text{ }\mu\text{m} \times 400\text{ }\mu\text{m}$ pixel [2]. The active edge region is made with a perimeter trench filled with p^+ silicon, making the sensor efficient to within a few microns of the physical edge [7]. The sensors are arranged with separate edge-biasing pads and electrode readout pads which allow simultaneous readout of two leakage currents. The edge-biasing pads provide the total leakage current, which includes contributions from the electrodes, surface, and active edges of the sensor. The electrode readout pads are isolated from the surface currents, which allows them to read out the electrode leakage current only.

Six identical sensors were studied. These included three that were not irradiated sensors (Sensor1, Sensor2, and Sensor3), and three sensors (Sensor4, Sensor5, and Sensor6) irradiated at the LANSCE facility, Los Alamos National Laboratory, with 800 MeV protons. A list of the devices along with their respective irradiation levels is shown in Table 1. These fluences are relevant to inner tracking environments anticipated for LHC upgrades.

Device	Fluence received (cm^{-2})
Sensor1	0
Sensor2	0
Sensor3	0
Sensor4	2×10^{15}
Sensor5	1×10^{16}
Sensor6	2×10^{16}

Table 1: 3D sensors used in this study, and their integrated dose received, in 800 MeV protons. The 1-MeV-neutron equivalent dose can be obtained by multiplying by the hardness factor, which is 0.7.

2.2 Setup

The setup for measuring leakage currents and sensor breakdown as a function of humidity is shown in Figure 1. Reverse bias voltage (V_{bias}) is applied to the sensor's edge pad with the Keithley 237 Source Measure unit, which also provides the measurement of the total (electrode, surface, and edge) current. The electrode current is measured from the electrode readout pads with the Keithley 617 Electrometer. The thermal chuck on which the sensor rests maintains a constant temperature of 24°C (Sensor1) or 20°C (Sensor2, Sensor3) for the unirradiated sensors and 10°C for the irradiated sensors (Sensor4, Sensor5, Sensor6). The humidity generator saturates the environment around the sample with water vapor by passing dry air - of 10% relative humidity - over water

59 within an enclosed reservoir, then flowing the air over the sensor. Relative humidities
 60 less than 10% are produced by flushing the sensor environment with a controlled flow
 61 of N_2 . Relative humidity is monitored with a Sensirion Model SHT71 humidity detector
 62 within the sensor environment.

Figure 1: (a) A photograph of one of the sensors. The electrode readout pads (columns pads), shown along the bottom, are joined together. A negative bias voltage is applied to the edge biasing pad, visible in the lower left-hand corner, to deplete the device. (b) The experimental setup for measuring leakage current as a function of bias voltage for controlled humidity variations.

63 2.3 Procedure

64 Two studies were conducted, both at constant temperature: (1) current stability ver-
 65 sus bias voltage, for 2 humidity conditions, and (2) breakdown voltage versus relative
 66 humidity.

67 To study the operational stability over time of a typical unirradiated and a typical
 68 irradiated sensor of this design, Sensor1 (unirradiated) and Sensor6 (irradiated) were
 69 held for 7-8 hours at 0.1% RH (with N_2) and then at 40% RH while measurements of
 70 leakage current versus bias voltage (IV) were taken approximately once per hour. Both
 71 leakage currents (total and electrode) were measured while the sensors were reverse
 72 biased, with V_{bias} ramped up in 1 volt increments from 0 V until breakdown occurred.
 73 For the purposes of this study, breakdown voltage is determined as the V_{bias} step after
 74 the leakage current reaches three times the value of the current at the midpoint of the
 75 linear current region. The result of this study is given in Section 3.1 below.

76 During the measurement of breakdown voltage versus relative humidity, the two
 77 leakage currents are recorded simultaneously and the sensor temperature is held constant.
 78 The measurements are repeated as the relative humidity of the sensor environment is
 79 varied from 0.1% to 80% in approximately 5% increments. At each humidity increment
 80 the RH of the environment around the sample is held for approximately 1 hour before
 81 the IV measurement is performed. The result of this study is given in Sections 3.2 and
 82 3.3 below.

2.4 Systematic Uncertainties

Errors intrinsic to the setup configuration include uncertainties produced by probe placement and resolution of data acquisition. The total systematic uncertainty on the leakage current is 1.91%. The total uncertainty on the breakdown voltage is less than 3.5%. A summary of all uncertainties is shown in Table 2. The fluences of the irradiated sensors are known to a precision of 15%.

Uncertainties	Leakage Current	Breakdown Voltage
Keithley 237	$\pm(0.035\% + 60\text{nA})$	$\pm(0.033\% + 24\text{mV})$
Keithley 617	$\pm(0.25\% + 10\text{pA})$	-
Temperature $\pm 0.3^\circ\text{C}$	0.003%	0.3%
Setup Configuration	1.89%	3%
Total	1.91%	$< 3.5\%$

Table 2: Sources of uncertainty on the measured leakage current and breakdown voltage.

3 Experimental Results

3.1 Stability

Figure 2 shows the results of the current stability study. The magnitude of the breakdown voltage of an unirradiated sensor remains constant during measurements taken over 8 hours of immersion in a controlled humidity environment. Its breakdown voltage diminishes by 20% (from 100 ± 2 V to 80 ± 2 V) when the relative humidity is increased from 0.1% to 40%. The magnitude of the breakdown voltage of a sensor irradiated to 2×10^{16} 800 MeV protons/cm² rises by about 5% during the first hour of its immersion in the controlled humidity environment. During the subsequent 7 hours of the test, its breakdown voltage continues to rise linearly at a rate of about 1 V per hour. Raising the RH from 0.1% to 40% produces an 18% reduction in breakdown voltage (from 184 ± 4 V to 146 ± 5 V). Note that proton irradiation increases the breakdown voltage of this sensor geometry by 60 - 80 V for the range of humidity values studied.

3.2 Leakage Current

Figure 3(a) shows a set of measurements of the electrode current of Sensor1 versus bias voltage, for eleven levels of relative humidity. These curves are representative of the data taken for all three unirradiated sensors. Below the breakdown voltage, the electrode current grows with bias voltage by less than a factor of two and shows no dependence upon relative humidity.

The electrode current in Sensor5 versus bias voltage is shown in Figure 3(b), again for several humidity values. These are representative of the data taken for all of the

Figure 2: Breakdown voltage as a function of time for two humidity and integrated fluence conditions. The size of the symbols covers the uncertainty in the measurement.

Figure 3: (a) Unirradiated Sensor1 electrode current as a function of bias voltage, at constant temperature of 24°C, for eleven levels of relative humidity from 13% to 65%. (b) Irradiated Sensor5 electrode current as a function of bias voltage, at the constant temperature of 10°C, for ten levels of relative humidity from 0.1% to 50%.

110 irradiated sensors. Similarly to the case with the unirradiated sensors, the electrode
 111 current shows no dependence upon relative humidity below breakdown.

112 3.3 Breakdown Voltage

113 The electrode currents in Figure 3(a) show a “knee” characteristic in the region of the
 114 bias breakdown voltage. As the relative humidity increases, the knee moves to the
 115 left; i.e, the electrode breakdown voltage decreases. Table 3 presents the reduction in
 116 breakdown voltage observed for each of the six sensors over the full range of relative
 117 humidity studied. Figure 4 shows the change in V_{BD} at each humidity step relative to
 118 V_{BD} at the minimum RH recorded for that sensor. One sees that although the irradiated
 119 sensors begin with a 60-80 V “advantage” in V_{BD} at low humidity, their breakdown point
 120 diminishes with increasing RH with a steeper characteristic than that of the unirradiated
 121 devices.

Device	ΔV_{BD} (V)	RH Range
Sensor1	18	13%-65%
Sensor2	26	0.1%-65%
Sensor3	31	0.1%-80%
*Sensor4	54	0.1%-70%
*Sensor5	25	0.1%-50%
*Sensor6	38	0.1%, 40%

Table 3: The humidity-induced decrease in breakdown voltage, ΔV_{BD} , and the humidity range studied for each sensor. The humidity ranges are slightly different for each sensor due to their particular points of current instability at high RH. The uncertainty on each value of ΔV_{BD} is approximately 3%. The irradiated sensors are indicated by a * next to their name.

122 4 Discussion

123 As is shown in the ISE-TCAD simulations in [9], the 3D sensor breakdown is caused
 124 by avalanche breakdown at the surface near the p^+ electrode, where the electric field
 125 reaches its maximum value. We note (see [3, 5]) that negative charges arising from the
 126 humid environment settle at or near the surface of the oxide. As explained in [1, 2],
 127 these charges drift along electric field lines that loop outside the sensor between the n^+
 128 and p^+ electrodes on the oxide surface until they aggregate around electrodes of the
 129 opposite sign. Simulations in [9] show that this condition increases the electric field near
 130 the p^+ electrode when a large potential difference is created between the charges on the
 131 outer surface of the oxide and the p^+ electrode. These negative surface charges also
 132 compensate the effects of the positive charges inside the oxide, decreasing the density of
 133 electrons at the Si-SiO₂ interface to the point of allowing the depletion region to reach

Figure 4: The decrease in breakdown voltage of the sensors as a function of increasing relative humidity. Data for Sensor6 are not available. The irradiated sensors are indicated by a * in the legend.

this realm. Here the surface generation process contributes charge carriers to the high electric field region, leading to avalanche breakdown at the junction [9].

5 Summary

Leakage current and reverse breakdown in 3D silicon sensors have been examined over a range of relative humidity from 0.1% to 80% for both irradiated and unirradiated samples. As relative humidity is raised from a few percent to 50% or higher, the total leakage current increases by approximately an order of magnitude while the electrode leakage current remains approximately constant, suggesting that the current increase originates at the surface. This effect is independent of fluence received. The breakdown voltage is found to be constant, regardless of relative humidity, over the period from one to 8 hours of operation in a controlled temperature and humidity environment. Irradiation of the samples with 800 MeV protons to integrated fluences in the range of 2×10^{15} to 2×10^{16} 800 MeV protons per cm^2 raises their breakdown voltage by about 60-80 V, independent of humidity. Direct comparison of the rate of decrease of breakdown voltage as a function of increasing RH suggests a stronger characteristic decrease in irradiated than unirradiated 3D sensors of this design.

6 Acknowledgements

This work was supported by the U.S. Department of Energy and the National Science Foundation. Use of the LANSCE irradiation facility was provided by Los Alamos National Laboratory.

References

- [1] S.I. Parker, C.J. Kenney, J. Segal, Nucl. Instr. and Meth. A 395 (1997) 328-343.
- [2] Sherwood Parker, et al., Nucl. Instr. and Meth. A 685 (2012) 98-103.
- [3] A. Longoni, M. Sampietro, L. Struder, Nucl. Instr. and Meth. A 288 (1990) 35-43.
- [4] A. Chilingarov, D. Campbell, G. Hughes, Nucl. Instr. and Meth. A 560 (2006) 118-121.
- [5] M. Laakso, P. Singh, P.F. Shepard, Nucl. Instr. and Meth. A 327 (1993) 517-522.
- [6] F. G. Hartjes, Nucl. Instr. and Meth. A 552 (2005) 168-175.
- [7] Cinzia DaVia, Mario Deile, et al., IEEE Transactions on Nuclear Science 56 (2009) 505.
- [8] C. J. Kenney, et al., Nucl. Instr. and Meth. A 565 (2006) 272-277.
- [9] J. Kalliopuska, S. Eränen, R. Orava, Nucl. Instr. and Meth. A 568 (2006) 27-33.