Silicon Sensor Irradiation Studies for the LHC HL Upgrade

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This thesis by Andrew Thomas Kent is accepted in its present form by the Department of Physics as satisfying the thesis requirement for the degree of Master of Science.

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Date Ulrich Heintz, Advisor

Recommended to the Graduate Council

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Date Andrew G. Campbell, Dean of the Graduate School

This work is dedicated to my parents, Zaida Soriano and Ron Kent.

Acknowledgements

I am very grateful to have had many people help me along the way in my pursuit of an education in physics, and I especially wanted acknowledge a few of those who especially helped me with my goals.

Before arriving at Brown University I received extensive mentoring from Distinguished Professor of Physics at UCLA, George Morales - we would meet every week for a few hours and he would teach me what it meant to be a theoretical physicist and how one should go about solving very difficult problems. I will always look back fondly on those meetings I had with him.

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I would like to thank Professor Ulrich Heintz for allowing me to learn in his lab as a laboratory assistant and also for his guidance in writing this thesis, my time working in his lab has been a wonderful education.

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Abstract

Hello, this is my abstract

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1.1 The Large Hadron Collider

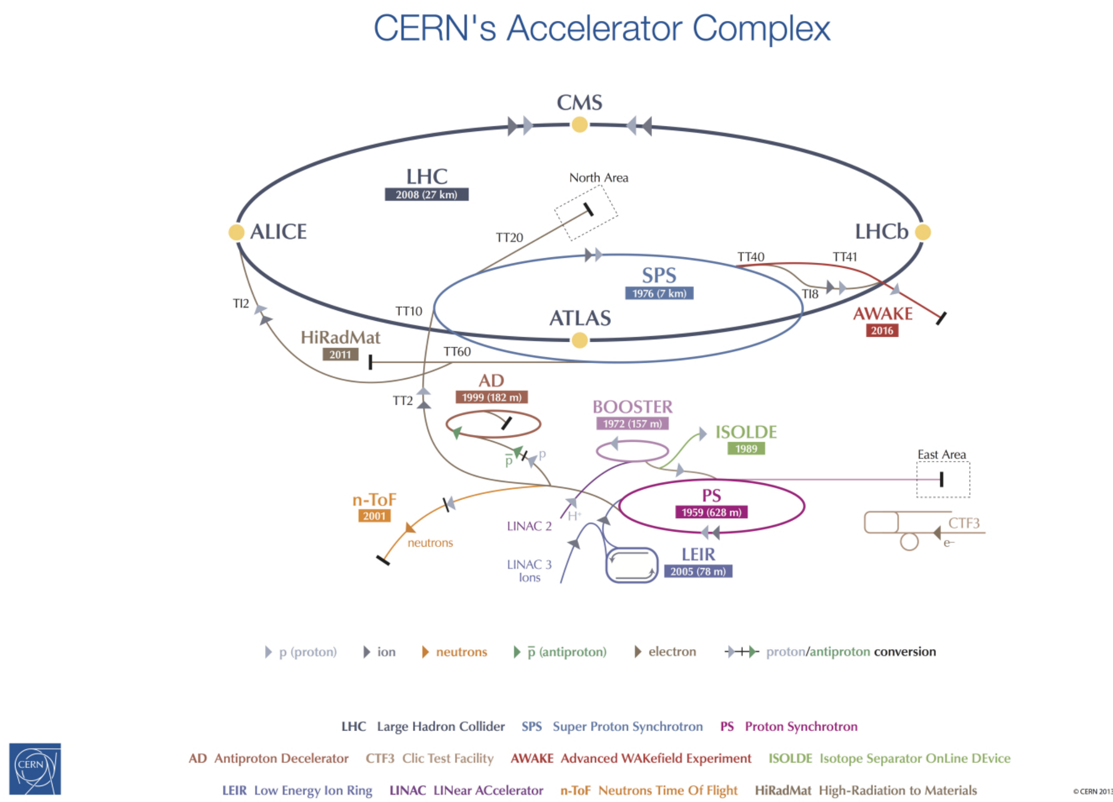

Figure 1.1: CERN Complex (from [1])

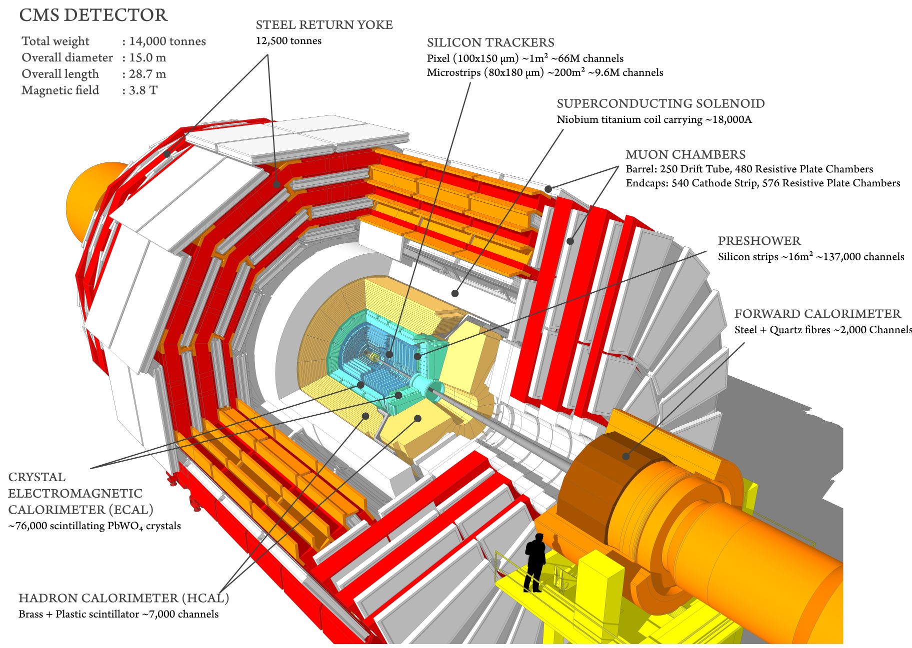

Figure 1.2: CMS Detector Diagram (from [8])

1.1.1 The High-Luminosity Large Hadron Collider (HL-LHC)

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1.2.1 Silicon Sensors

1.2.1.1 Strip Sensors

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1.2.2 The Muon tracker

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Chapter 2

Silicon Detectors

2.1 Silicon Sensor Properties

In figure 2.1 (a) shows Intrinsic silicon, (b) shows a n-type Si with donor (phosphorus). Finally in (c) we see a p-type Si with acceptor (boron).

2.1.1 Basic Sensor Traits

Applying a bias voltage V in the reverse direction to the sensor, the thickness of the depletion charge region is given by

$$w(V) = \sqrt{\frac{2\epsilon_0\epsilon_{Si}}{e}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V+V_{bi})} \tag{2.1}$$

where V_{bi} is the so-called built-in-voltage, N_A is the the concentration of acceptor atoms, N_D is likewise the concentration of donor atoms, ϵ_0 is the permittivity of vacuum and ϵ_{Si} is the permittivity of silicon where $\epsilon_{Si}/\epsilon_0 \approx 11.8$. Typically V_{bi} is usually insignificant compared to the bias applied to the sensors so we cal approximate the depletion region as

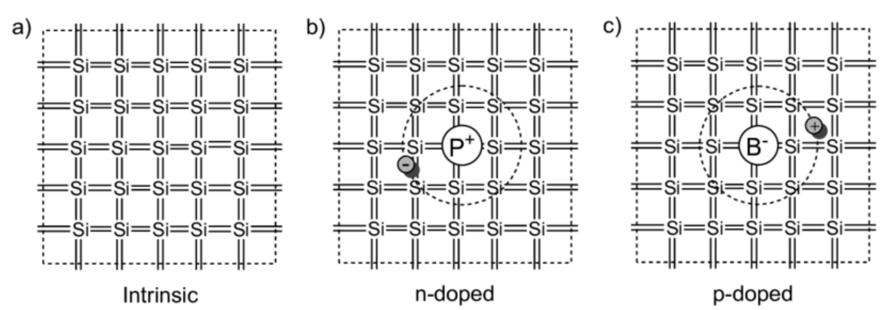

Figure 2.1: Example of doping in Silicon (from [6])

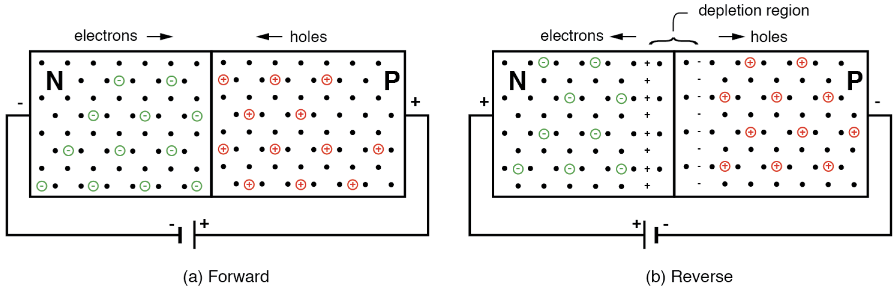

Figure 2.2: Silicon Sensor Depletion Region (from [3])

$$w(V) \approx \sqrt{\frac{2V\epsilon_0\epsilon_{Si}}{eN_D}} \tag{2.2}$$

Now, in order to utilize the entire piece of silicon for detecting particles we need to expand this depletion region over throughout the entire thickness of the silicon detector. The voltage at which this is achieved is called the depletion voltage (V_{dep}) and is given by

$$V_{dep} = \frac{eN_Dd^2}{2\epsilon_0\epsilon_{Si}} \tag{2.3}$$

2.1.2 PN Junction

In figure 2.2 (a) shows the forward bias repels carriers toward the junction, where recombination results in applied voltage current. While in (b) it shows the reverse bias attracts carriers toward applied bias terminals, away from the junction.

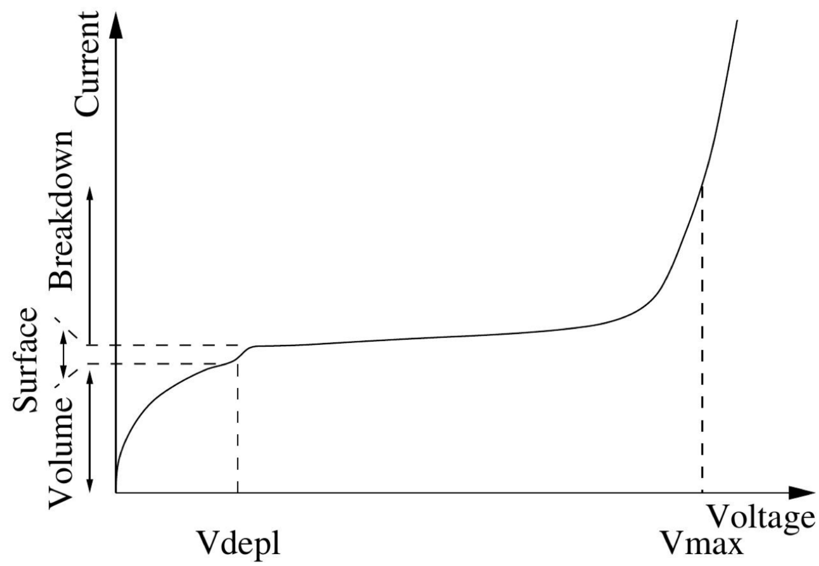

Figure 2.3: Typical IV Curve (from [7])

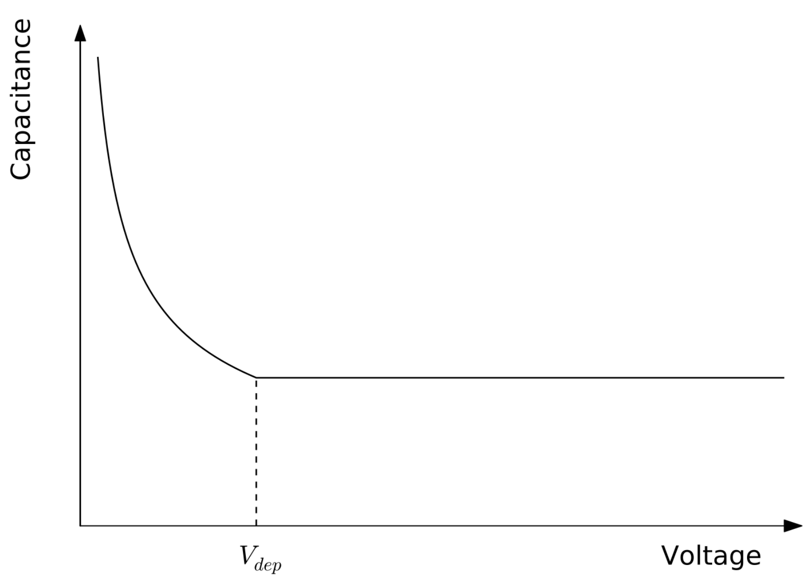

Figure 2.4: Typical CV Curve (from [7])

Chapter 3

Radiation Damage

3.1 Bulk Silicon Damage

displacement damage of a particle fluence (Φ) can be expressed as the 1-MeV neutron equivalent fluence (Φ_{eq}) as

$$\Phi_{eq} = \kappa\Phi \tag{3.1}$$

3.2 Annealing

3.2.1 Leakage Current

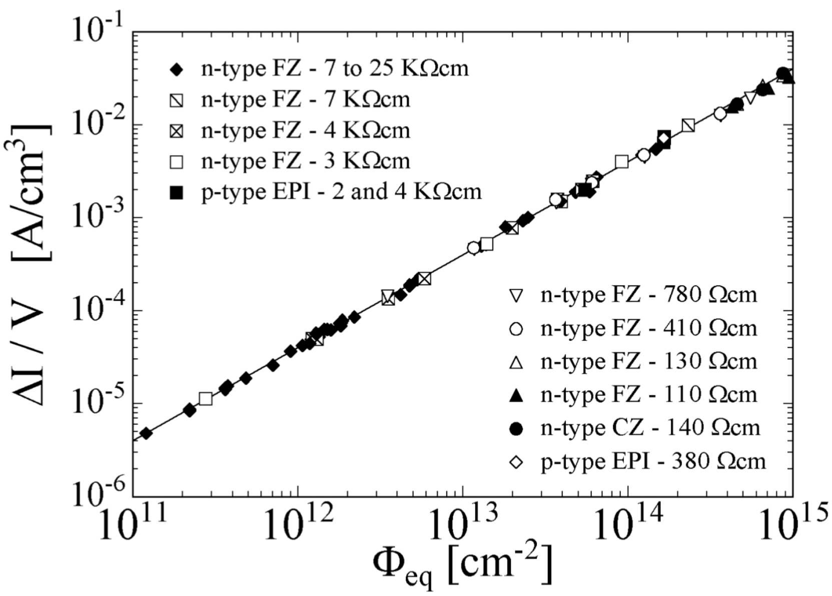

Figure 3.1: Fluence Dependence of Leakage Current for Silicon Detectors (from [5])

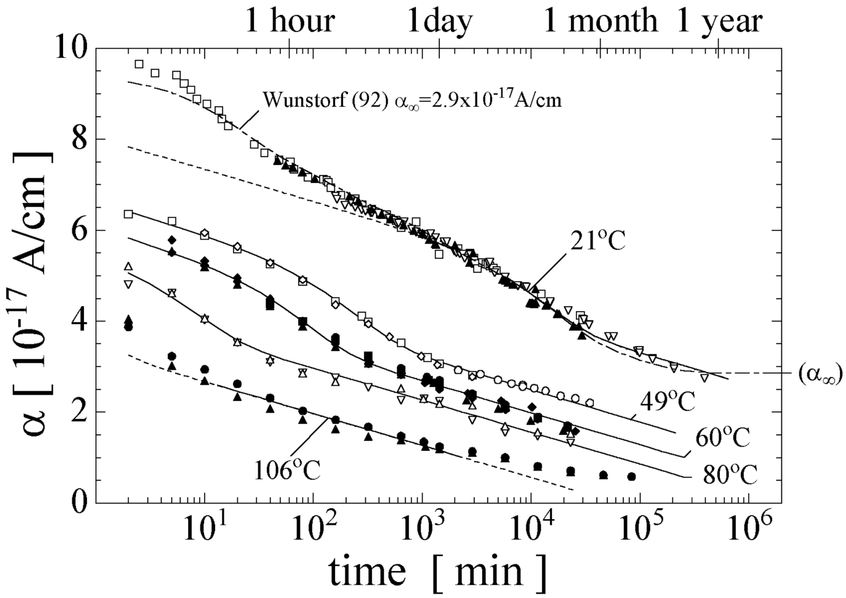

Figure 3.2: Current Related Damage Rate α as a Result of Cumulated Annealing Times at Different Temperatures (from [5])

$$\Delta I = \alpha \Phi_{eq} V \tag{3.2}$$

Where in our fluence analysis we are using a value of $\alpha = 3.99 \cdot 10^{-17}$ which M. Moll [4] showed to work well for annealing values of 80 min at 60C.

3.2.2 Effective Doping Concentration N_{eff}

the time dependence of N_{eff} can be parametrized as

$$\Delta N_{eff}(t) = N_C + N_A(t) + N_Y(t) \tag{3.3}$$

3.2.3 Hamburg Annealing Model

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7.1.1 PIN Diodes

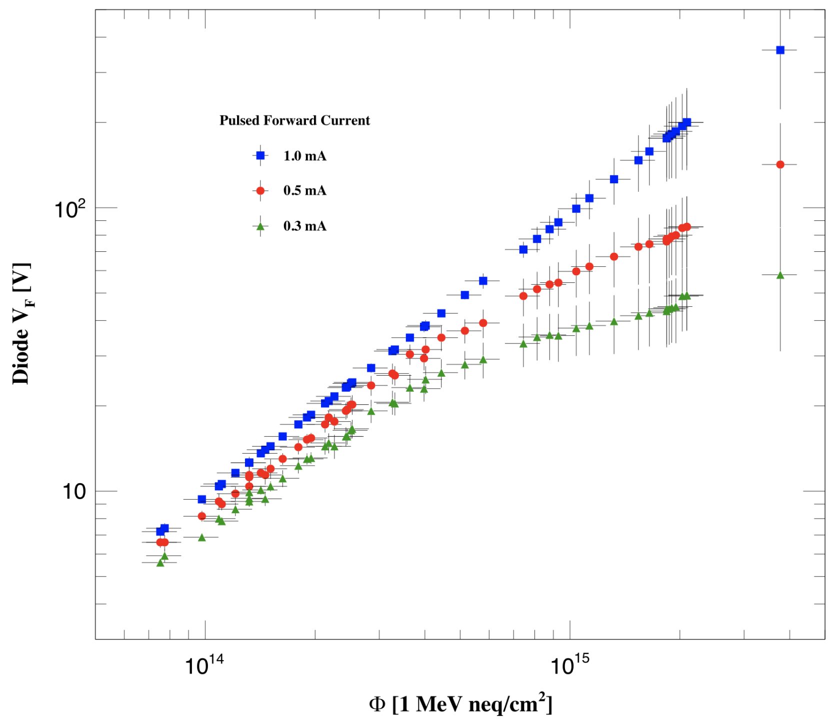

Figure 7.1: PIN Fluence Studies at Different Pulsed Currents (from [2])

In Figure 7.1 from the paper by Hoeferkamp et al. [2], we see diode forward voltage as a function of applied fluence, for three choices of applied current amplitude. The vertical error bars indicate the combined uncertainties related to temperature variation during the irradiation process, current pulse width, and sourcemeter precision. The horizontal error bars indicate the uncertainty deriving from counting statistics on calibration foils in the gamma spectrometer.

Based on the linear fit of Figure 7.1, Hoeferkamp et al. showed a good relation between diode forward voltage and fluence, where the forward voltage was measured after applying a $1mA$ for approximately .38s. That relation is seen in Equation 7.1.

$$\Phi_{neq} = 1.1 \cdot 10^{13} \cdot V_f - 6.2 \cdot 10^{10} \tag{7.1}$$

7.1.2 Depletion Voltage Calculation

7.1.3 Current Temperature Conversion

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7.2.1 Ljubljana Diodes

7.2.2 HGCAL Diodes

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8.1.1 PINs

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8.1.3 HGCAL

8.2 Affects of Concurrent Annealing and Irradiation

8.3 RINSC Ljubjana Cross Calibration

8.3.1 Silicon Damage Constant

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[7] Leonardo Rossi et al. *Pixel detectors: from fundamentals to applications*. Particle acceleration and detection. Berlin: Springer, 2006. DOI: 10.1007/3-540-28333-1. URL: https://cds.cern.ch/record/976471.

[8] Tai Sakuma. 'Cutaway diagrams of CMS detector'. In: (May 2019). URL: https://cds.cern.ch/record/2665537.

Appendix A

Code Used

1. GitHub CMS Folder:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor

2. Annealing Temperature Conversion:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor/tree/main/Diodes/DZero/Annealing_Conversion

3. HGCAL Hamburg Analysis:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor/tree/main/Diodes/HGCAL/Hamburg_Analysis

4. Alibava Annealing Studies:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor/tree/main/Diodes/Halfmoon/Annealing

5. Ljubljana vs. Rinsc Analysis:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor/tree/main/Diodes/Ljubljana_Diodes

6. Pin Diodes:

   https://github.com/AndrewTKent/CERN_CMS_Silicon_Sensor/tree/main/Diodes/Pins