CERN Project Report

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August 11, 2017

1 Introduction

Over the last nine weeks I worked with the inner tracker (ITk) development program for the phase 2 upgrade of the ATLAS inner detector. The goal of this program is to test pixel detector prototypes to be used in the ATLAS Inner Tracker (ITk) to ensure they meet the demands of the experiment. My work consisted of measuring the transfer functions of different pixel types, doing analysis on data from X-ray fluorescence measurements, and helping to develop a temperature and humidity monitoring system that will be used in some of the testing setups.

2 Transfer Functions

2.1 Background

The pixel sensor being developed and tested is a monolithic CMOS sensor.[1] As a charged particle traverses the sensor, it ionizes the sensor as shown in Figure 1.[2] An electric potential across the depletion region around the N-wells causes the electrons to drift towards the N-well diodes.

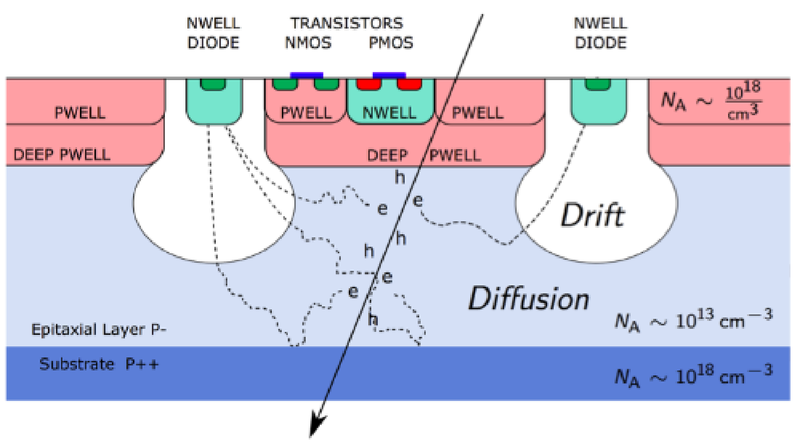

Figure 1: Cross Section of the Sensor

This results in an induced change in the electric potential at the sensing node in Figure 2. In this image the sensor is represented by the diode D_1 in Figure 2. This voltage change is transferred via the circuitry connected to the sensing node, the amplifier circuit, to the output where it is read by readout electronics,

[1] H. Pernegger et al., "First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors," CERN, (2017), http://iopscience.iop.org/article/10.1088/1748-0221/12/06/P06008/pdf

[2] Image taken from H. Pernegger et al., "First tests of a novel radiation hard CMOS sensor process for Depleted Monolithic Active Pixel Sensors," CERN, (2017), http://iopscience.iop.org/article/10.1088/1748-0221/12/06/P06008/pdf

in our case, an oscilloscope or a volt-meter. The transfer function of the sensor describes the relationship between the potential at the sensing node, and the output. It is desirable that this relationship be linear, to ensure that the signal is not getting distorted. The CMOS sensor consists of 134 different substructures which differ in geometrical and analog circuitry properties (i.e. pixel spacing, electrode size, reset mechanism, and others). Each such substructure is a matrix of 8x8 identical pixels that can be read out simultaneously.

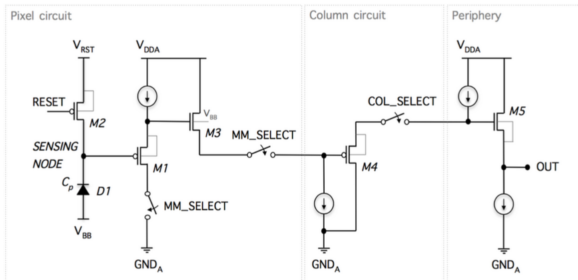

Figure 2: Schematic of the Front End of a Pixel

2.2 Setup and Methods

To measure the transfer functions, we we set the depletion voltage, V_{BB} in figure 2, equal to 0 and ramp up the voltage at the sensing node (which is referred to as the input voltage) from 0V to 1.8V in steps of 0.05V, and we measure the output voltage. The depletion voltage is the voltage that causes the charges to drift to the N-well diodes in Figure 1. The sketch below shows the setup used to take the measurements.

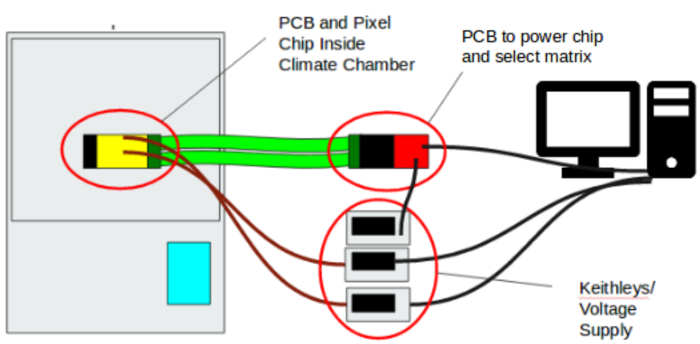

Figure 3: Transfer Function Measurement Setup

It was necessary to use a climate chamber, depicted by the gray box at the left in Figure 3, to provide a stable cold and dry environment for the measurements. The temperature needed to be low (for these measurements we used -30 °C), because the irradiated chips must be kept cold to minimize annealing. In order to prevent condensation or crystallization on the chip, we needed to have a dry environment. This was provided by blowing dry air into the climate chamber. We placed the pixel chip therefore, connected to a PCB inside of a climate chamber (represented by the yellow rectangle in Figure 3). This is connected to another PCB outside the climate chamber (represented by the red and black rectangles in Figure 3), powered by a power supply, and connected to the computer. The PCBs are used to select the matrix and to power the pixel according to the commands given by the computer. A second power supply connected to the computer is used to provide the input voltage. The latter is controlled by the computer. A volt-meter reads the output voltage from the pixel sensor and relays it to the computer. The computer then collects the data and stores it.

2.3 Measurements

First we measured the transfer function of several matrices of an unirradiated chip to serve as our standard. Figure 4 below shows the transfer function of one of these matrices.

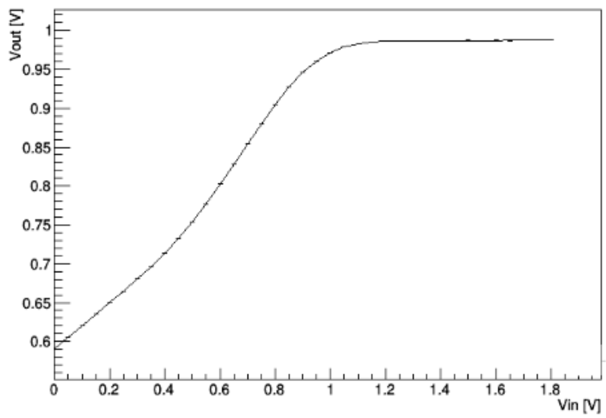

Figure 4: Transfer Function of a Matrix

As expected, we see a linear region in the relationship between the input and output voltages until the saturation level of the amplifier circuit is reached (above 1 V). We also tested the stability of our setup by taking 500 measurements from the same matrix, and comparing them to each other. These measurements are all plotted in Figure 5.

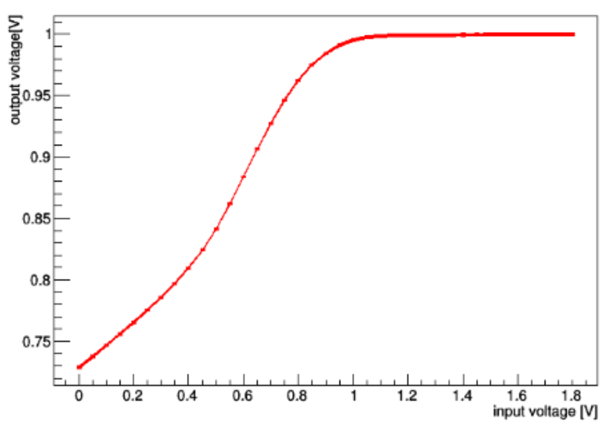

Figure 5: 500 Transfer Function Measurements of the Same Matrix

From Figure 5 we see that the setup is very stable, giving us reproducible measurements. This allows us to conclude that any changes observed in the transfer functions are not due to systematic uncertainties or failures in the setup. Having measured the transfer functions of the unirradiated matrices, we measured the transfer functions of matrices with the same characteristics from chips that had been irradiated to a fluence of 10^{14} 1 MeV neutron equivalent to observe how the irradiation affects the amplifier circuit. Below is an example of the transfer function of an irradiated chip compared to the transfer function of the unirradiated chip. This example shows the same characteristics that we observed for all the matrices that were used in the measurements.

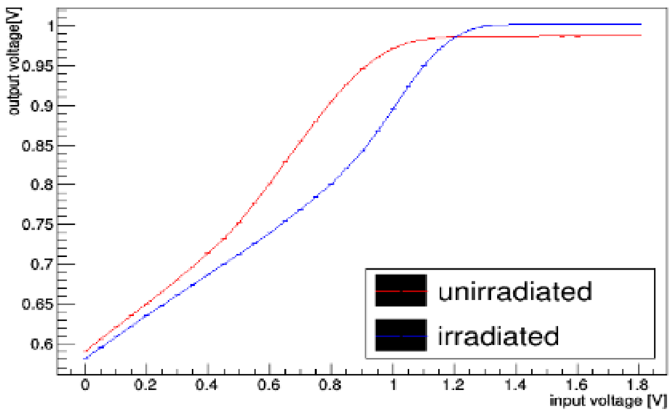

Figure 6: Transfer Functions of Unirradiated and Irradiated Matrices

2.4 Results and Conclusions

We observed that after irradiation a linear relationship still remained between the input and output voltages. We also noted that the output voltage decreased, causing the saturation level to be reached at a higher input voltage. In addition, the saturation level increased. Being the first measurements of this kind done with this chip, we didn't know what to expect. The analyzed structures are simple for a CMOS pixel sensor but still more complex than a single transistor. For this reason, the results will be further discussed with the chip designers in order to understand the observed behaviour. In addition, further tests can be carried out using chips that have been exposed to different levels of irradiation.

3 Fluorescence Setup

3.1 Background

To test the energy linearity and amplification of the different pixel structures, we use monochromatic light over a range of different energies. The monochromatic light is generated as follows. An X-ray vacuum tube is used to ionize the atoms in a target. Electrons from higher energy shells can then fill the vacancy. In this process, they emit light of a characteristic energy. This effect is known as fluorescence. A setup to do this was built. This setup is shown in Figure 7.

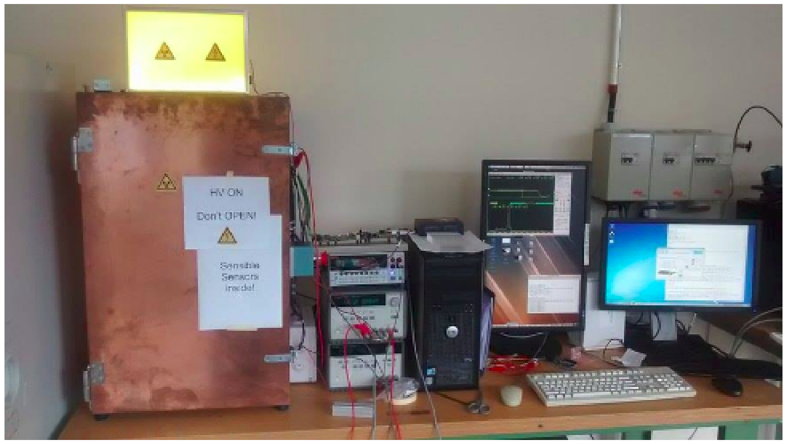

Figure 7: Setup for the Fluorescence Measurements

Inside the copper box there is an X-ray source, emitting X-rays onto a target material (like copper, iron, or titanium). The pixel chip connected to a PCB is placed underneath the target to detect the light from the target, as shown in the diagram below.

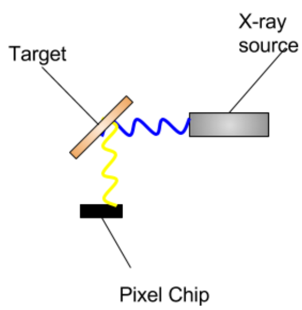

Figure 8: Diagram of the Fluorescence Measurement Setup

A power supply is used to power the X-ray source, which is controlled by the computer. Another power supply provides the sensor bias voltage. This is V_{BB} in Figure 2. Another power supply is used to power the PCB outside of the copper box, as well as an amplifier placed inside the copper box. The PCB outside the copper box is connected to the PCB inside the box and together they are used power the sensor and select the matrix to be measured. The output voltage from the sensor passes through the amplifier inside the copper box, and then it is read by an oscilloscope. The oscilloscope saves the signal to the computer whenever a threshold voltage is exceeded.

3.2 Measurements

The first thing we did was to measure the background noise of the box. This was done by measuring the RMS of the baseline read by the oscilloscope with the X-ray source off, meaning no light was being detected by the sensor. The mean values that we obtained reading from matrix 106 were 3.8 mV with the copper target, 3.65 mV with the iron target and 3.67 mV with the titanium target. The uncertainties on the noise measurements have not yet been determined. After measuring the noise, we turned on the X-ray source, and ran measurements reading from 4 different matrices, and recording 60000 wave forms for each matrix. This was done with each of the targets mentioned (copper, iron, and titanium).

3.3 Analysis

Once the measurements were taken, we graphed each wave form and performed a fit on it. The fit was used to calculate the height of the signal, which was then plotted on a histogram. This way we could recreate the energy spectrum of the measurement. Figure 9 shows an example of a spectrum. The peaks on the right correspond to the K_α and K_β energies of the fluorescent radiation. The peaks of the histogram were then fitted with Gaussian curves as shown in Figure 9 to calculate the means, which can now be plotted against the known values of the energies of the fluorescent radiation from the targets we used. From this we can check the linearity of the gain of the sensors.

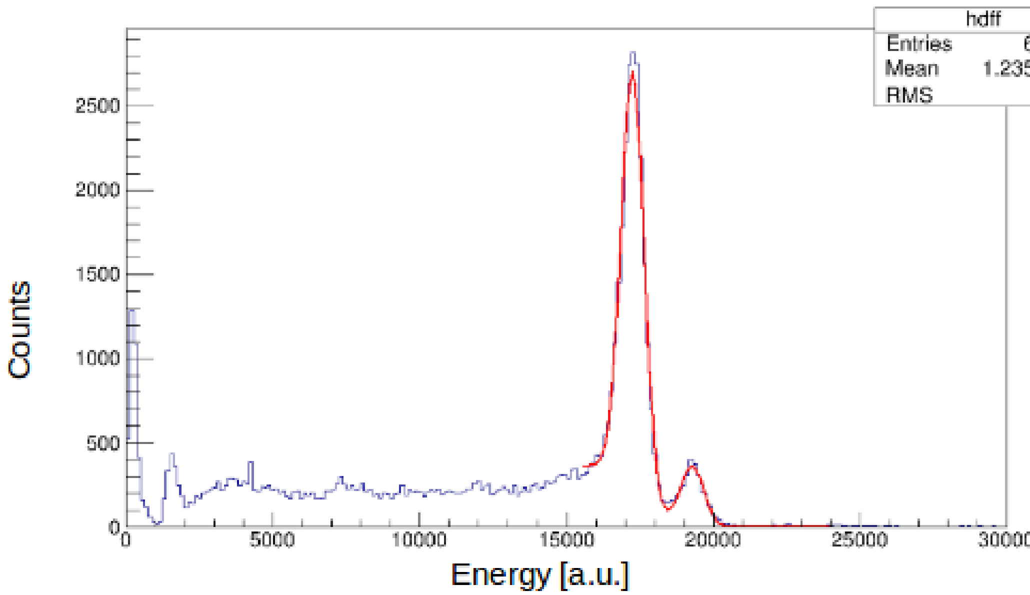

Figure 9: Example Energy Spectrum from Fluorescence Measurements