Operation, Calibration, and Characterization of a Silicon Pixel Detector Through Junction Capacitance Measurement and Signal Analysis Using a Radioactive ^{90}Sr Source

Aleksandar Tuzlak
atuzlak@ethz.ch
ETH Zürich, D-PHYS
May 5, 2025

In this experiment we determine the depletion voltage of a silicon diode through a junction capacitance measurement. Moreover with the same detector a signal analysis has been performed using a radioactive ^{90}Sr source to assess the validity of the calculated depletion voltage. Additionally an algorithm for the calibration of a PROC600 readout chip was implemented. After carrying out the experiment we have for the depletion voltage $V_d = 46 \pm 4$V. We conclude that the experimentally obtained values align with the theoretical model. The experiment was performed successfully and the calibration of the readout chip was achieved but extensive error analysis on the experiment setup to reduce systematic errors and a more descriptive model for the calculation of the depletion voltage as well as greater datasets will lead to more accurate results.

A pixel detector is found for example in the innermost part of the Compact-Muon-Solenoid detector, a particle detector, situated at the Large Hadron Collider in Cern, Geneva. They consist of many layers, each containing readout chips (ROCs) for several pixels. [1]

In this experiment, the sensor is a silicon diode operated under a high reverse-bias voltage V_{bias}, which increases the width of the depletion region of the pn-junction leading to a greater possibility of particle detection. For instance, when a particle is traversing the depletion region, generation of electron-hole pairs occurs, which are then accelerated due to the large bias voltage V_{bias} generating a small signal current collected on the detector capacitance

$$C_D = \sqrt{\frac{\varepsilon_0 \varepsilon_r}{2\rho\mu|V_{bias}|}} A \tag{1}$$

where ρ : specific resistivity, μ : mobility of majority charge carriers and A : detector surface, ε_0: permittivity of free space, ε_r: relative permittivity.
If the depletion zone reaches the edge of the sensor we speak of full depletion i.e. one would expect the detector capacitance to be approximately constant above a certain bias voltage.
Using an equivalent AC circuit acting as a high pass filter with $f = 1$MHz being above the cutoff frequency to decrease overall attenuation and get a higher gain. This allows us then to rewrite Eq.(1) to

$$C_D = \frac{\frac{V_{out}}{V_{in}} C_P}{1 - \frac{V_{out}}{V_{in}}} \tag{2}$$

where $C_P = 3.9$pF: oscilloscope probe capacitance, V_{in}, V_{out} : input/output peak-to-peak voltage

In a final step the signal is amplified and can then be read out by the detector electronics (ROC). In order to do so, the pixel sensor has to be calibrated such that a compromise between non-detected particles and a tolerable level of noise hits is established. This is a consequence of the manufacturing process resulting in variations of doping and impurity concentrations leading to different values of baseline, noise and threshold for each pixel.
Furthermore if there is still noise present in the signal, one can use a so-called shaper which is essentially a bandpass filter. [2]

Methods

The purpose of this experiment is to understand the operation and characterization of silicon pixel detectors by measuring their electrical properties, observing particle-induced signals, and calibrating readout electronics for accurate particle detection.

In order to achieve this a silicon diode is used as a detector operated under a reverse-bias voltage V_{bias} in a first step. Applying a bias voltage requires the following AC setup reduced to a capacitively loaded high pass filter to measure the detector capacitance C_D (for the general setup see Appendix A.4).

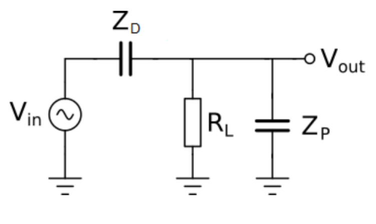


Fig. 1 | AC setup used to measure the detector capacitance C_D. Z_P : probe impedance, R_L : load resistance, Z_D : detector impedance.

Since a high pass filter configuration is used, the measurement requires a high frequency AC signal which is set to 1MHz. Thus allowing us to measure the detector capacitance C_D for bias voltages $V_{bias} \in [0, 90]$V using Eq.(2). Furthermore by plotting $\frac{1}{C_D^2}$ against V_{bias} one can identify two approximately linear regions. Additionally performing a linear fit to each region and extrapolating the intersection point of the two linear fits allows to determine the voltage at which total depletion is reached V_d.

In a second step we measure the signal induced by a radioactive ^{90}Sr source. Due to tiny signal currents in the sensor, the signal is amplified by a preamplifier (see Appendix A.4) and then passed through a bandpass filter a so-called shaper to reduce the noise level. A particle hit is then registered if the signal exceeds a certain threshold which can be varied at a specific bias voltage V_bias. To establish a good compromise between noise and signal, several shaper configurations are tested first.

Fig. 2 | Shaper configuration used to measure the particle hits of the ^{90}Sr source:
Highpass: $C = 100\text{nF}$, $R = 100\Omega$
Lowpass: $C = 100\text{nF}$, $R = 2.2\text{k}\Omega$
The upper figure shows the filtered amplified signal of the ^{90}Sr source for a particle hit and the lower figure shows the noise level for the given shaper configuration.

Additional shaper configurations that were not further used in the experiment can be found in Appendix A.2.
Particle hits and noise were measured for different bias voltages $V_{bias} \in \{30, 60, 90\}$V and a threshold range of $[50, 250]$mV for 20s each since at too high thresholds, no hits are registered and for too low thresholds mainly noise is measured. Therefore a good threshold region for the sensor at a particular bias voltage needs to be established.

In a final step we need to calibrate the readout chip (PROC600). The chip consists of 52 by 80 pixels but for simplicity the GUI (Pyxar Mini) used to calibrate the chip only shows 4 by 4 pixels. The calibration is done with a comparator, which compares the output of the preamp to a configurable threshold and puts out a high potential if the signal crosses this threshold. Ideally one would need to only set one global threshold value but due to manufacturing processes the baseline, noise and threshold vary across the chip. Therefore the configurable threshold will be different for each pixel which needs to be accounted for. Hence the goal is to level out all the different threshold values to a global one by setting a global threshold first and then trimming each individual pixel. The calibration code for the readout chip can be found in Appendix A.3.

Data Analysis and Results

If not mentioned otherwise, the uncertainties of the values are calculated using Gaussian error propagation. (see Appendix A.1).
No further error analysis or measurements have been performed on the silicon pixel detector itself nor the radioactive source to assess their quality or reliability.

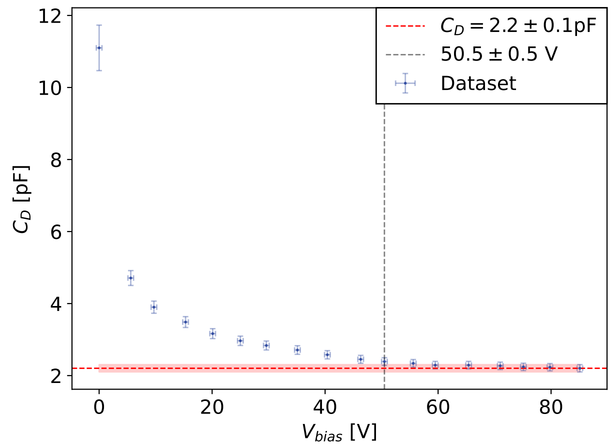


Fig. 3 | Measured junction capacitance C_D of the silicon diode as a function of the bias voltage V_{bias} using Eq.(2). Marked in red is the value of the last datapoint i.e. the junction capacitance $C_D(V_{bias} = 85.1 \pm 0.5\text{V})$. All the values for the junction capacitance measured for higher bias voltages than the indicated vertical dotted black line at $V_{bias} = 50.5 \pm 0.5\text{V}$ are within the uncertainty of the last datapoint suggesting a linear behavior.

Using the first dataset we can now plot C_D^{-2} again as a function of the bias voltage V_{bias}. We do this in order to be able to extract then from this relation through linear fits of two approximately linear regions which then allows us to calculate the depletion voltage by the extrapolated intersection point which is found to be at $V_d = 46 \pm 4\text{V}$.

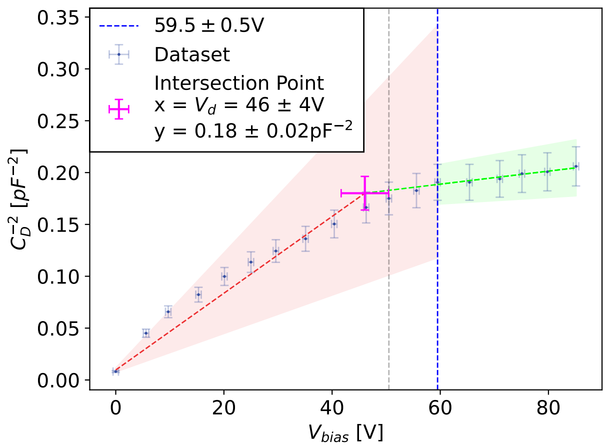


Fig. 4 | C_D^{-2} as a function of the bias voltage V_{bias}. The two approximately linear regions have been identified on either side of the blue dotted line at $V_{bias} = 59.5 \pm 0.5\text{V}$. The red and green dotted lines indicate the linear fit for the

corresponding region including the error of the fit indicated by the shaded area in the respective color. Extrapolating the fit from the green region allows us to find the intersection point of the two linear fits, the depletion voltage indicated in purple which is found to be at $V_d = 46 \pm 4$V. Additionally the dotted black line at $V_{bias} = 50.5 \pm 0.5$V from the dataset in Figure 3 above is included and is within the uncertainty of V_d.

Lastly the signal induced by the radioactive ^{90}Sr source i.e. the number of hits for a specific threshold voltage as well as the noise level was measured.

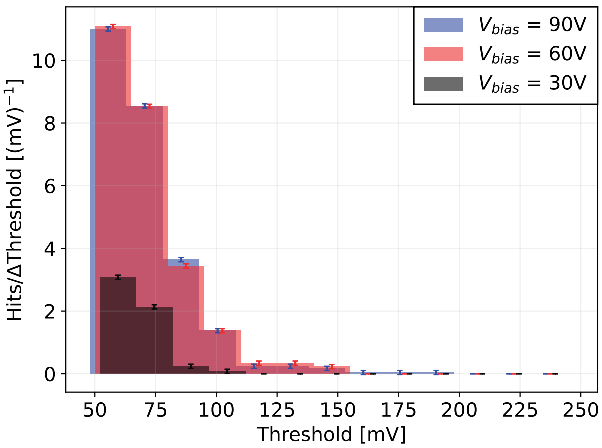


Fig. 5 | Measured number of hits per change of the threshold voltage as a function of the threshold voltage plotted in a histogram. The number of hits without the source, i.e. registered hits from noise levels is implicitly included in this figure but since the background is very small compared to the signal itself not explicitly indicated.

Discussion of Results

From the junction capacitance measurement we can conclude that the silicon diode is fully depleted at a bias voltage of $V_d = 46 \pm 4$V. This is in good agreement with the expected value of $V = 50.5 \pm 0.5$V for which the silicon diode capacitance did not change significantly for higher bias voltages. Since the identification of the two linear regions in Figure 4 was only estimated, this introduces an additional systematic error to the depletion voltage V_d. Nevertheless the acquired data agrees with the theoretical model. For the signal analysis of the ^{90}Sr source at bias voltages higher than the calculated depletion voltage V_d we can see that the values are within the same uncertainty, and therefore behave equivalently as expected. Furthermore the detection rate for smaller bias voltages where full depletion has not occured is smaller which also agrees with the theoretical model.

Additionally, since no error analysis on the sensor nor the radioactive source regarding quality and purity has been performed the errors are expected to be larger than calculated. Hence a greater dataset with smaller measurement steps and greater integration time for the signal analysis as well as more shaper configurations is going to lead to a more precise assessment of the silicon detector and consequently the underlying theory. Furthermore during the measurements we experienced some grounding issues which very likely introduced systematical errors at some point.

Finally the calibration of the readout chip was performed successfully. The algorithm used to level out the thresholds of the pixels was able to converge within less than 10 iterations every time.

Conclusion

In this experiment we determine the depletion voltage of a silicon diode through a junction capacitance measurement. Moreover with the same detector a signal analysis has been performed using a radioactive ^{90}Sr source to assess the validity of the calculated depletion voltage. We have found that theoretical predictions were found to lie within the uncertainty of our experimental results.

There are nevertheless some limitations to the experiment. The measurements were performed with a limited number of shaper configurations and bias voltages. Additionally no extensive error analysis on the sensor nor the radioactive source regarding quality and purity has been performed as well as ensuring proper grounding at all times during the experiment. Furthermore the identification of linear regions should have been performed multiple times with different parameters and consequently a slightly different classification. This leads to a greater uncertainty in the results than calculated.

To conclude, error analysis on the experiment setup to reduce systematic errors as well as more precise classification of linear regions i.e. a more descriptive model and more data points will lead to more accurate results.

Acknowledgments

The execution of the experiment in the laboratory was supported in part by Julian Stumpf[1] and Chen Xie[2].

References

1. CERN. *The CMS Experiment* Accessed: 2025-04-05. 2025. `https://home.cern/science/experiments/cms`.
2. Xie, C. & Burkhalter, S. *ASL Instructions for Pixel Detector Experiment* Accessed: 2025-04-05. 2022. `https://vp.phys.ethz.ch/Experimente/pdf/ASL_instructions_pixel.pdf`.

[1]jstumpf@ethz.ch
[2]chexie@phys.ethz.ch

A Appendix

A.1 Calculation of Uncertainties Using Gaussian Error Propagation

For uncorrelated variables $x_1, x_2, ..., x_n$ with uncertainties $\sigma_{x_1}, \sigma_{x_2}, ..., \sigma_{x_n}$ and a function $f(x_1, x_2, ..., x_n)$, the uncertainty of f is given by

$$\sigma_f = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right)^2 \sigma_{x_i}^2} \tag{3}$$

A.2 Waveform of Readout Electronics Measurement for Different Bandpass Configurations

The images were taken before a grounding issue was discovered therefore they are accompanied with additional noise, but since the noise level on its own was not considered the waveform nevertheless shows the effect of the different bandpass filter configurations accurately enough. Upper line: raw amplified signal,lower line: filtered amplified signal.

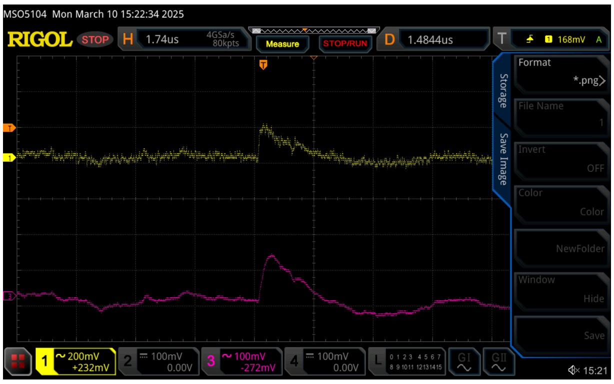


Fig. A.2.1 | Highpass: $C = 100\text{nF}$, $R = 470\Omega$
Lowpass: $C = 100\text{nF}$, $R = 2.2\text{k}\Omega$

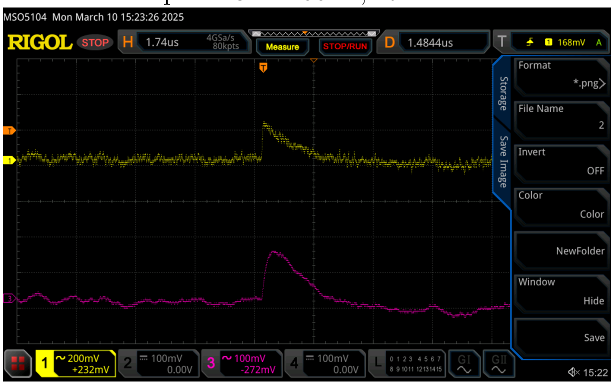


Fig. A.2.2 | Highpass: $C = 470\text{nF}$, $R = 470\Omega$
Lowpass: $C = 100\text{nF}$, $R = 2.2\text{k}\Omega$

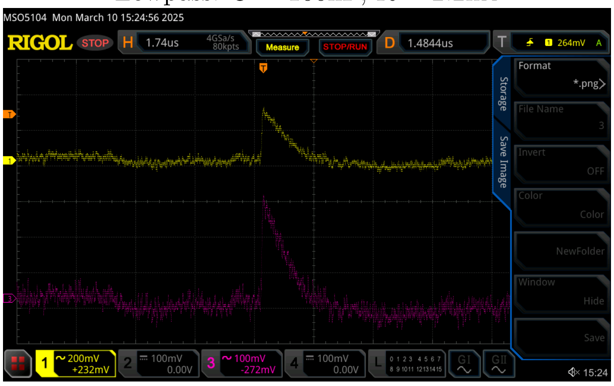


Fig. A.2.3 | Highpass: $C =$ short, $R = 470\Omega$
Lowpass: $C = 47\text{nF}$, $R =$open

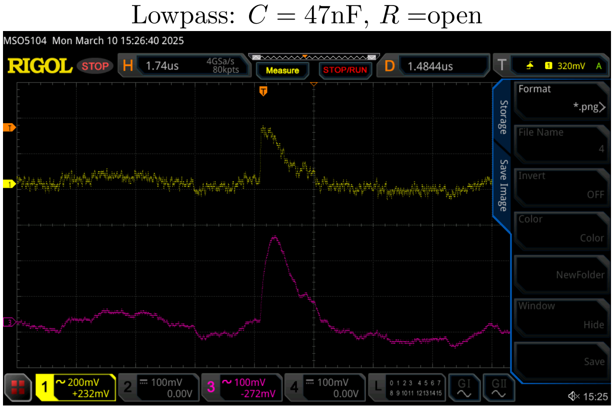


Fig. A.2.4 | Highpass: $C = 470\text{nF}$, $R = 33\Omega$
Lowpass: $C = 100\text{nF}$, $R = 2.2\text{k}\Omega$

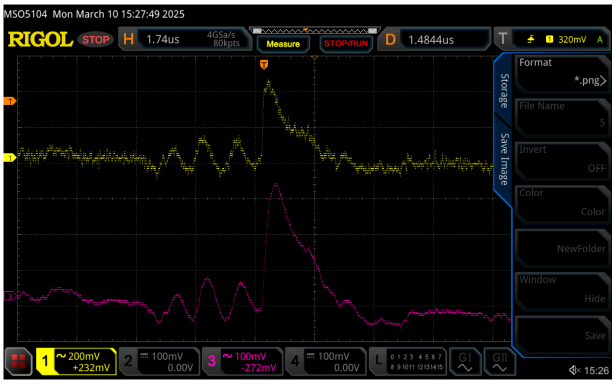


Fig. A.2.5 | Highpass: $C = 470\text{nF}$, $R = 33\Omega$
Lowpass: $C = 47\text{nF}$, $R = 2.2\text{k}\Omega$

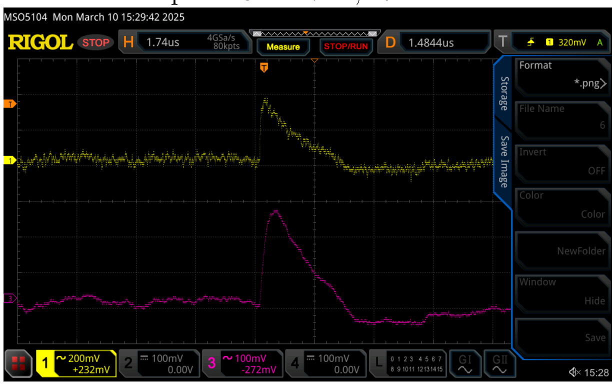


Fig. A.2.6 | Highpass: $C = 470\text{nF}$, $R = 470\Omega$
Lowpass: $C = 1\text{nF}$, $R = 2.2\text{k}\Omega$

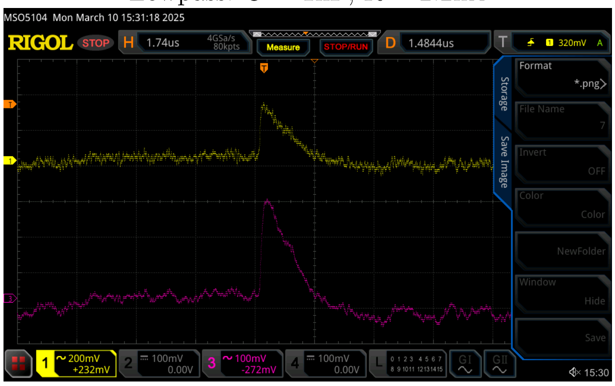


Fig. A.2.7 | Highpass: $C = 100\text{nF}$, $R = 470\Omega$
Lowpass: $C = 1\text{nF}$, $R = 680\Omega$

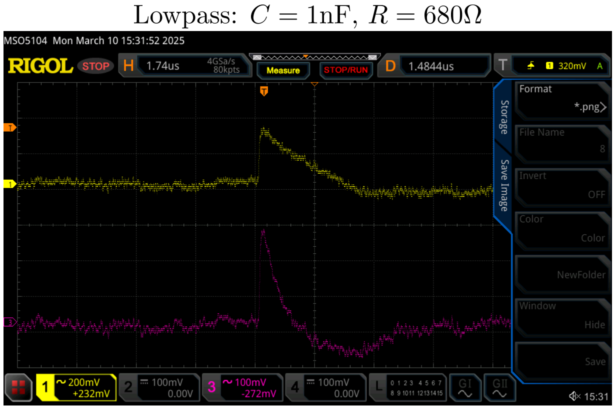
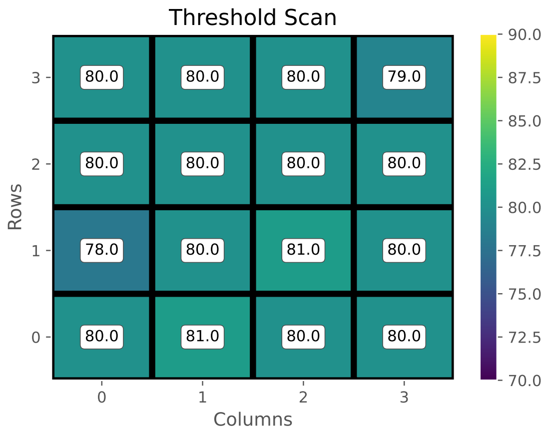


Fig. A.2.8 | Highpass: $C = 10\text{nF}$, $R = 470\Omega$
Lowpass: $C = 1\text{nF}$, $R = 220\Omega$

A.3 Operation and Calibration Code for the PROC600 Chip - on_trim_routine()

The following code is used to perform the trimming of the PROC600 chip. It is part of a larger script that can be found in the appendix. The code is written in Python and uses the PyXar library to communicate with the chip. The function `on_trim_routine()` is responsible for the trimming process. It first resets all pixels to untrimmed, then performs a threshold scan to determine the initial threshold values. The function then adjusts the threshold values to ensure that the minimum value is greater than 80 Vcal. Finally, it trims the individual pixels based on their threshold values.



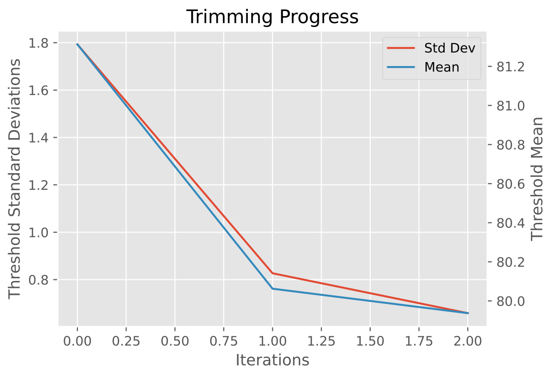


Fig. A.2.1 | The left figure shows the threshold scan of the PROC600 chip after our calibration algorithm was applied and indicates a successful implementation of leveling out the thresholds to 80vcal units. The right figure shows the iteration progress of the trimming process, where the mean and standard deviation of the threshold values are plotted against the number of iterations. The mean value converges to 80 Vcal, while the standard deviation decreases, indicating that the thresholds are being leveled out and that in only 3 iterations in this case specifically. Furthermore the number of iterations required until termination never exceeded 7 with our algorithm and different starting global threshold values.

```python
def on_trim_routine(self):

    self.reset_trim() # set all pixels to untrimmed
    self.on_resetDac()
    self.threshold_means = []
    self.threshold_stds = []
    vtrim_initial, vthrcomp_initial = self.read_dacs() # store initial value of DACs
    vtrim = vtrim_initial
    vthrcomp = vthrcomp_initial
    vthrcompStep = 1

    self.on_thresholdscan() # perform initial scan
    # the thresholds are now saved in the list self.thresholds

    t = self.thresholds

    tMin = np.min(t)
    tMax = np.max(t)
    iMin = np.where(t == tMin)
    iMax = np.where(t == tMax)


    # adjusting threshold such that the minimum value is >80vcal
    while tMin < 80:
        # adaptive threshold step-change
        rangeThresholds = 80 - tMin
        vthrcompStep =  rangeThresholds if rangeThresholds > 20 else 10 if rangeThresholds
            > 10 else 8 if rangeThresholds > 5 else 4 if rangeThresholds > 3 else 1

        vthrcomp -= vthrcompStep

        self.write_dacs(vtrim, vthrcomp)

        self.on_thresholdscan()
```

```
        t = self.thresholds
        tMin = np.min(t)
        tMax = np.max(t)

        # Do this after every optimization step to get a progress in the end
        self.threshold_means.append(np.mean(self.thresholds))
        self.threshold_stds.append(np.std(self.thresholds))


    # trimming of the individual pixels
    # 80.05 to not undershoot the desired mean of 80 by too much
    while np.mean(self.thresholds) > 80.05:
        #creating a copy to have numpy toolset accessible
        copy = np.array(self.trims)
        #trimming, large deviations get trimmed more, smaller less
        copy[np.where(self.thresholds >= 90)] -= 5
        copy[np.where(self.thresholds >= 85)] -= 3
        copy[np.where(self.thresholds >= 81)] -= 1
        self.write_trim(copy)
        self.on_thresholdscan()

        self.threshold_means.append(np.mean(self.thresholds))
        self.threshold_stds.append(np.std(self.thresholds))


    print('means: ', self.threshold_means)
    print('stds: ',self.threshold_stds)
    print('trims: ',self.trims)
    print("Set vtrim to: {0}".format(vtrim))
    print("Set vthrcomp to: {0}".format(vthrcomp))

    return
```

The complete python script can be found here: pyxar_mini.py

A.4 Circuits

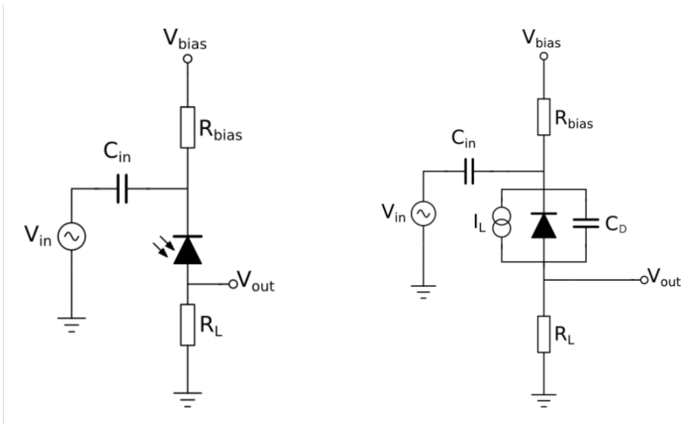


Fig. A.4.1 | General measurement setup used for the junction capacitance measurement (left) as well as an equivalent circuit (right).

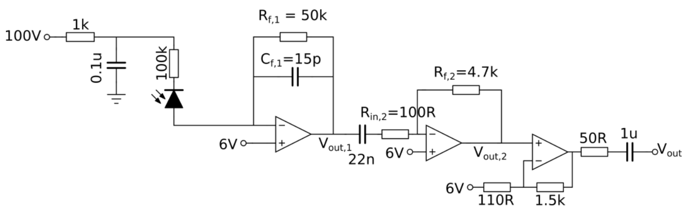


Fig. A.4.2 | Complete preamplifier circuit used to amplify the signal from the detector.