Semiconductor Detector Exercises

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1 Introduction

In the pn-junction, charge carriers diffuse through the border and form a region without free charge carrier, called depletion region. The size of this region can be increased by applying external reverse bias potential. To deplete the whole thickness of the semiconductor the full depletion voltage

$$V = \frac{qN_{eff}d^2}{2\epsilon}, \tag{1}$$

where N_{eff} is the effective space charge density, ϵ is the permittivity, d is the thickness of the material and q is the electron charge, needs to be applied. Full depletion is necessary for silicon detector to dissipate electron-hole pairs generated by traversing charged particle. If depletion is not full, the bulk will contain free charges which can't be distinguished from the pairs generated by the passage in the detector of charged particles.

In the present work an n-type silicon with a p-doped metallic region was used; the depletion voltage was determined in a clean environment to be ≈ 26 V.

Properties of a hand made pre-amplifier such as the gain, rise time and noise as a function of load capacitance have been studied, moreover the performance of a spectroscopy amplifier was investigated and a calibration curve defining correlation between the amplifier channels and number of electrons was obtained. A particle detector was built using the pre-amplifier and the diode previously characterized in the clean room environment and used to measure the spectrum of radioactive source ^{137}Cs.

2 Experimental setup

Basic experimental setup consisted of a home made pre-amplifier (a vero board with various inputs and outputs: grounding, input of the signal for the silicon sensor, Cal. in. input used for calibration, two inputs for -12V and +12V from power supply, grounding of the power supply and output), power supply and an oscilloscope. Figure 1 (left) shows a schematic view of the pre-amplifier with all the inputs/outputs (pins) identified.

In order to measure the pre-amplifier gain, rise time and noise as a function of load capacitance, the vero board was connected to a pulse generator and a power supply. The signal from the pulse generator and from the pre-amplifier were shown on the oscilloscope screen.

Then, the performance of spectroscopy amplifier was studied. The spectroscopy amplifier and pulse height analyzer (PHA) were added to the previous setup. The signal from the pulse generator was sent through the pre-amplifier to spectral amplifier and was displayed on PHA.

Finally, before the measurement of a radioactive source, a low-pass filter was built in the creative corner of the vero board in order to feed the voltage through it to the sensor, that was also put inside the vero board. In order to reduce noise, the whole box was shielded as long as the cables connecting it to the power supply. Figure 1 (right) shows part of this setup: the shielded pre-amplifier (in the box) and power supply; the pulse generator is also visible.

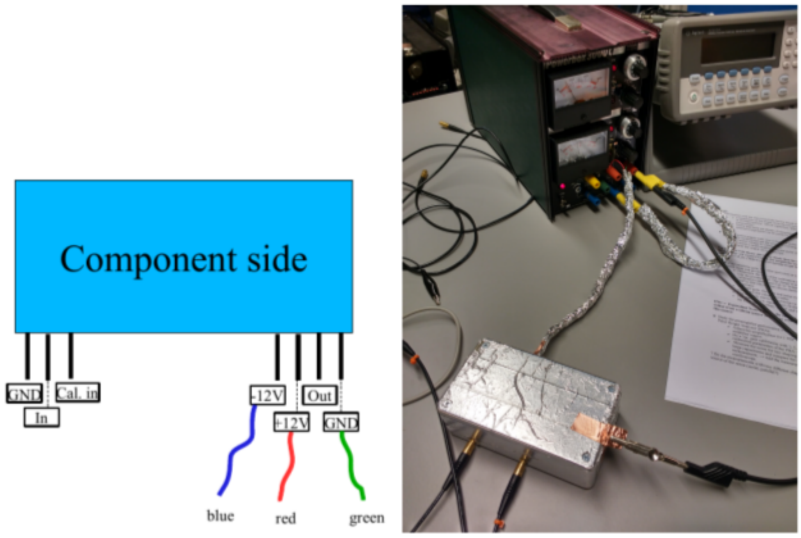


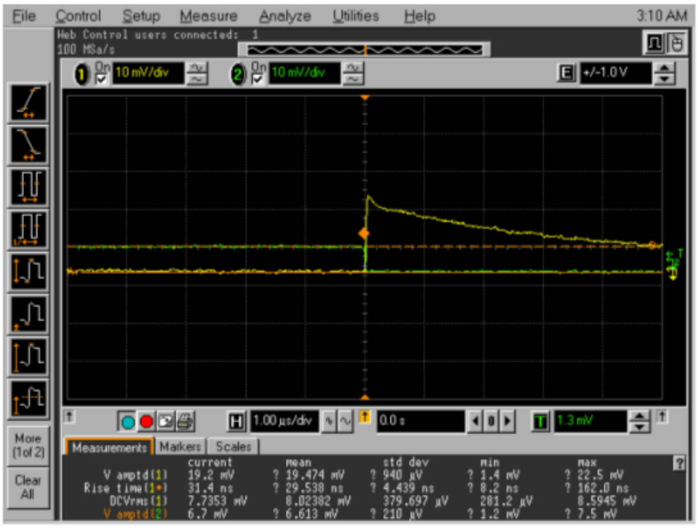
Figure 1: Left: Layout of the pre-amplifier board. Right: Experimental setup; power supply for the preamplifier and the closed vero board.

3 Preamplifier noise measurements

A square pulse from pulse generator was used to characterize the pre-amplifier (note to self: follow the guidelines in the manual that says that everything should be checked before proceeding, you might end up with a preamplifier, that seems to be fried, even though it might have just been a loose cable). Figure 2 shows the response as displayed on the oscilloscope, in green the square pulse from the pulse generator and in yellow the response of the pre-amplifier. One can see that the pre-amplifier has an amplification factor of about 3 and that the injected square pulse has, after passing through the pre-amplifier, a tail due to the consecutive discharging of the capacitance.

For the source measurements we expect to see about 1-2 minimum ionizing particles (MIP) in 300 micrometer of silicon, which presumably corresponds to between 25000 and 50000 electrons. On Cal. in. there is a capacitor with $C_{\text{cal}} = 0.4$ pF, so to imitate the expected signal, we can send a square pulse into the preamplifier with an amplitude between 10-20 mV. In reality, the actual input voltage is decreased due to present resistance of 50 Ω in the circuit, which means that $U_{actual} \approx U_{input}/\sqrt{2}$. Thus, if the amplitude of the sent square pulse is $U_{input} = 10$ mV, the actual pulse that arrives into the amplifier will be roughly $U_{actual} = 6.5$ mV. Then, using the

U(actual) is because of the 50 Ohm termination.



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              current      mean          std dev       min          max
 V amptd(1)   19.2 mV    ? 19.474 mV   ? 940 µV      ? 1.4 mV     ? 22.5 mV
Rise time(1•) 31.4 ns    ? 29.538 ns   ? 4.439 ns    ? 8.2 ns     ? 162.0 ns
  DCVrms(1)   7.7353 mV    8.02382 mV    379.697 µV    281.2 µV     8.5945 mV
 V amptd(2)   6.7 mV     ? 6.613 mV    ? 210 µV      ? 1.2 mV     ? 7.5 mV
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Figure 2: Screen dump of oscilloscope with a square pulse from the pulse generator (green) and the pulse response from the preamplifier (yellow).

formula $Q = CV$, and dividing $Q/1.602 \times 10^{-19}$, one finally gets that 10 mV (1 MIP) corresponds to about 16500 electrons.

not 1MIP. You said on previous page that 1MIP is 25000 e-

With the test signal we want to determine the pedestal noise of the preamplifier, i.e. when it is unloaded. This has to be extracted from the noise when it is loaded. We generate a square pulse with an amplitude of 6.5 mV (as the precise voltage was not of dire importance, according to R.Brenner), and a long enough period. Then a number of test capacitors ranging from 1 - 100 pF were included step by step and the gain, rise time and noise RMS of the preamplifier output were determined. Note that the pre-amplifier already had an intrinsic capacitance of 0.4 pF. We used tools on the oscilloscope to determine the quantities, as can be seen in the bottom of Fig. 2. Some of the used values of capacitance had rather wildly fluctuating values. In Table 1 the values that seem to be the most prevailing are presented.

as long as the value is correctly used :)

Table 1: Characteristics of the preamplifier for various test capacitors.

C [pF]	Ampl. [mv]	Gain	t_{rise} [ns]	Noise RMS [μV]	ENC [elec.]
1	20	2.99	31	540	445
4.7	19	2.84	32	470	408
10	17	2.54	33	450	436
27	15	2.24	42	490	539
54	13	1.94	49	480	609
100	10	1.49	60	500	825

correct!

The presented values of gain, rise time and noise RMS in Table 1 are plotted as a function of load capacitance in Fig. 3-5. As the values were read from the oscilloscope screen, large uncertainties were assigned to the data, taken as 10% of the measured value. There is definitely an effect on the gain and rise time, though the noise level is somewhat fluctuating. Again, this can be mainly caused by the imperfect read out from the oscilloscope screen. This measurement might have been more useful if it had taken place with the final setup where plenty of steps were taken to reduce the noise level, such as shielding of the cables with aluminium foil.

Next, the Equivalent Noise Charge (ENC) had to be determined, which is the number of electrons one would have to collect from a silicon sensor in order to create a signal equivalent to the noise of the sensor. This was calculated according the formula:

$$ENC = \frac{U_{noise}}{U_{amplitude}} Q_{MIP}, \qquad (2)$$

YES!

where Q_{MIP} is the input charge to the amplifier corresponding to 1 MIP (corresponding to input voltage of 6.5 mV) which was calculated above as 16500. The resulting values are presented in the last column of Table 1.

In Fig. 6 the ENC values are shown as a function of the load capacitance. As can be seen from the fit, the pedestal noise is here estimated to be 410 ± 40 electrons and the noise slope 4 ± 1.

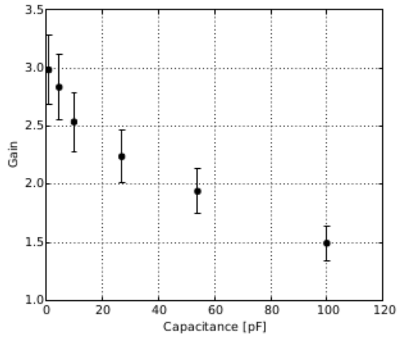

Figure 3: The gain as a function of load capacitance.

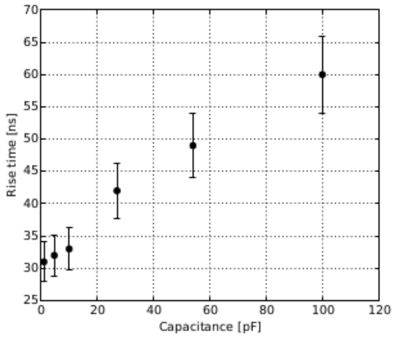

Figure 4: The rise time as a function of load capacitance.

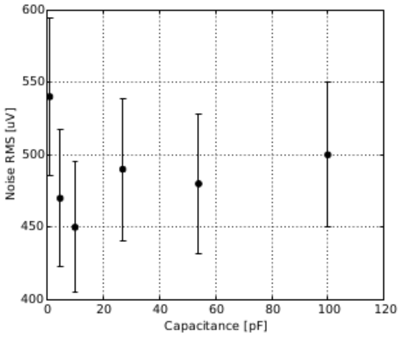

Figure 5: The noise RMS as a function of load capacitance.

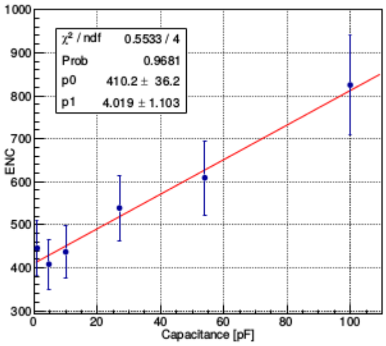

Figure 6: The ENC as a function of load capacitance.

Correct measurement, unfortunately a little high noise.

4 Spectroscopy amplifier performance

Next step was to understand the performance of the spectroscopy amplifier, which serves as shaper and also improves the signal to noise ratio. The signal from the preamplifier was sent to a spectroscopy amplifier, and was both observed on the oscilloscope and on the pulse height analyzer (PHA) with 2048 channels. The amplification on the spectroscopy amplifier was set to 1.5 V which roughly corresponds to 1 MIP.

In order to map the PHA channels to the output voltage of the spectroscopy amplifier, three test pulses with 1, 2 and 3 MIP were used to get the calibration function of the analysers. This approximately corresponds to 16000, 33000 and 50000 electrons.

In Fig. 7 the calibration spectrum for a shaping time of 2 μs and 8 μs are presented. Using the peaks from generator the calibration function $F(\text{ch})$ was determined, in the program.

$$F_{2\mu\text{s}} = 50.1 \text{ electrons} + \text{ch} \cdot 29.6 \text{ electrons} \tag{3}$$
$$F_{8\mu\text{s}} = 47.5 \text{ electrons} + \text{ch} \cdot 27.2 \text{ electrons} \tag{4}$$

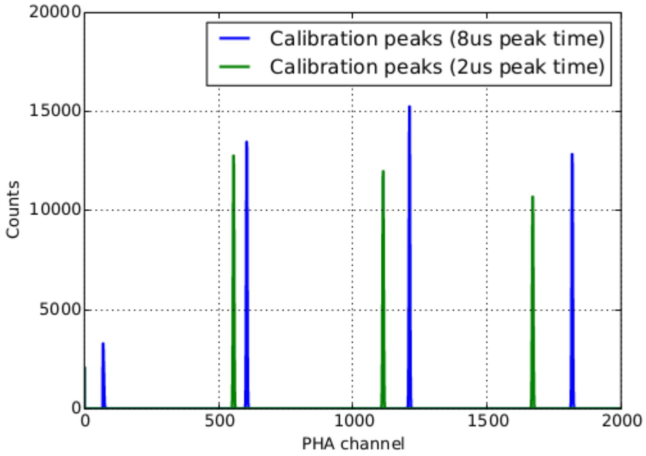

Figure 7: Calibration spectra for two shaping times in terms of PHA channels.

Calibration OK. You determine the ENC from the FWHM of the peaks.

5 Source measurement with Cs-137

Finally, a measurement of a Cs-137 using the semiconductor sensor was performed. Being one of the last groups to take this measurements, we benefited from many previous ideas for improvement. The source was put inside the preamplifier box, on a neat little stand. For illustration, a photo is shown in Fig. 8. Also, a low-pass filter was built on the creative corner of the vero board to feed the voltage bias through it to the sensor. The major problem seemed to be with noise, which was tried to be mend by shielding the setup. The box was closed, and connected to aluminium foil covering all the wires going in and out of the preamplifier box, and connected to a common ground on the power supply.

First of all it was possible to see a good signal on the oscilloscope, both before and after the spectroscopy amplifier. This is seen in Fig. 9.

Using the PHA, a number of pulses were collected with and without the source in the preamplifier box. In Fig. 10 the spectra are presented in terms of number of electrons, both with and without the source. One clearly sees that pulses start

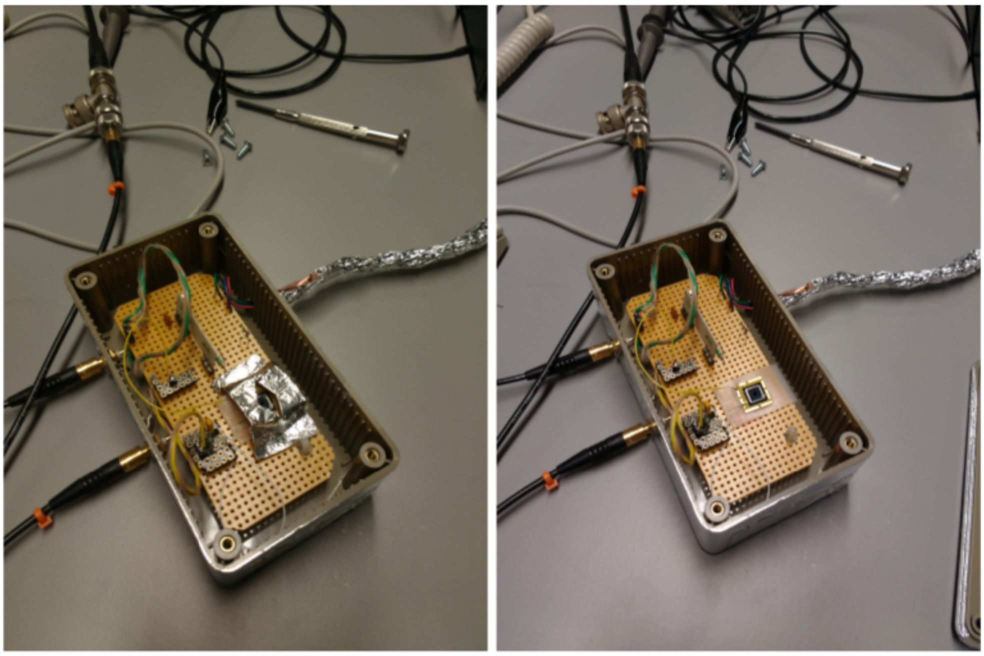

Figure 8: Photo of the experimental setup inside a vero board, together with the semiconductor sensor and a stand on top of it, made for the Cs-137 source.

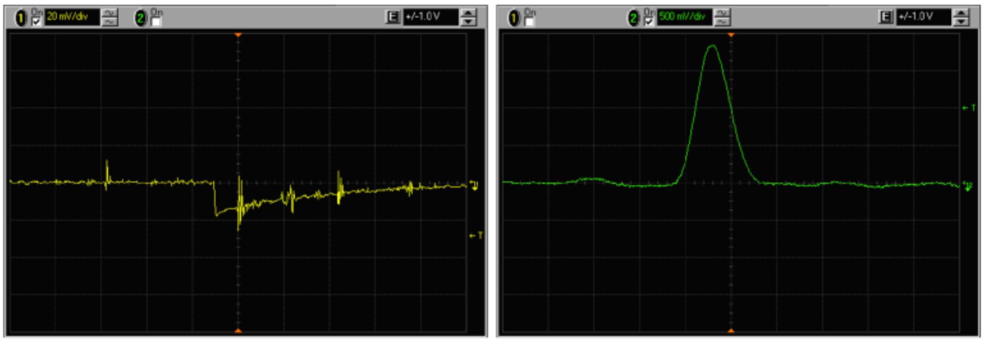

Figure 9: A pulse as seen on the oscilloscope from the preamplifier (left) and spectroscopy amplifier (right), that stems from a signal for the Cs-137 source.

showing up with pulse heights above the noise (responsible for the peak below PHA channel 100).

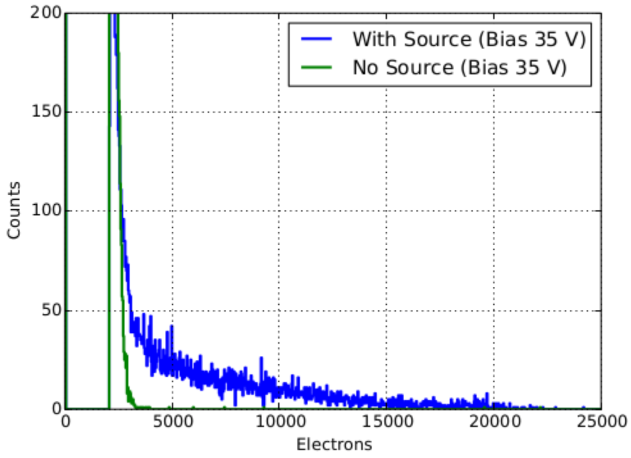

Figure 10: The spectra measured in terms of generated electrons in the silicon both with and without the source present.

The bias voltage on the semiconductor sensor was set to 35V, as from the clean room exercise the depletion voltage was found to be at about 26V. So with this bias voltage the detector should be fairly depleted. This we challenged by applying both a suboptimal and an overly conservative bias voltage of respectively 10V and 50V. In Fig. 11 it is shown that the response does not change dramatically by varying the bias voltage.

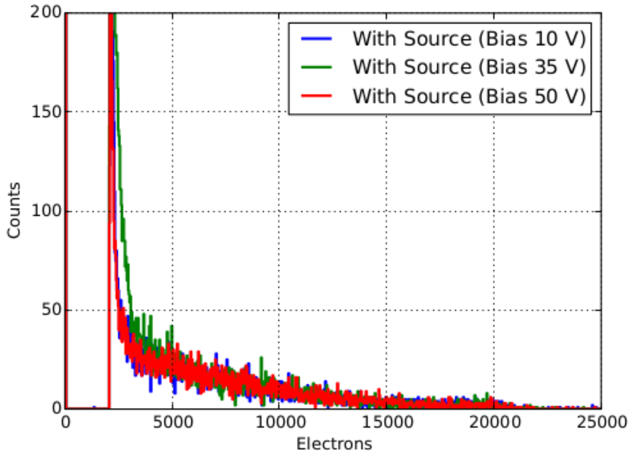

Figure 11: The spectra measured in terms of generated electrons for multiple bias voltages applied.

Unfortunately not great performance. For a successful spectra please have a look eg. A. Burgmans report.
We noticed that one of the two lab tables for some reason had higher noise :(
Noy a fault of the groups at the table. :)

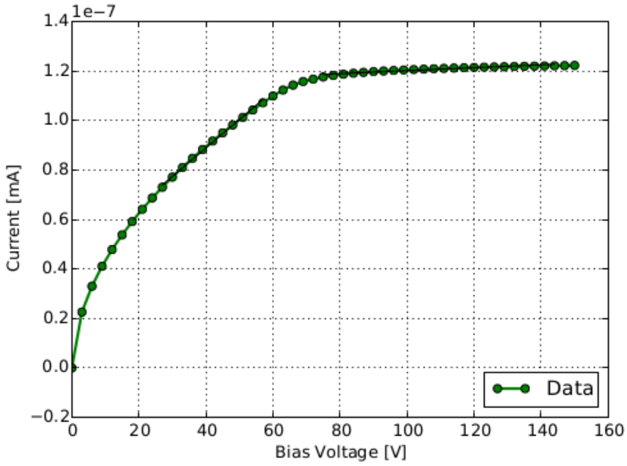

Figure 12: The resulting IV-curve for the simulated chip.

6 Simulation of diode from experiment

Finally, we used the GSS program to simulate the silicon chip we have been working with, find the IV-curve, and compare to the measurements we took in the clean room. The following parameters are listed about the silicon chip:

- Diode thickness: 300 mm
- Active area: 5 mm X 5 mm
- Bulk concentration n-type: 1E12 cm-3
- Implant concentration p-type: 5E18 cm-3
- Implant depth: 2 mm
- Thickness of Al metallisation: 0.5 mm

The chip is implemented as 300 micron thick, but only 50 micron wide, as an 5000 micron wide chip with the same number of mesh points took too much memory. The chip is simulated with a n-type bulk with a concentration of 1E12, as well as dopants on both sides with a concentration of 5E18. The thickness of the metallisation was not able to be implemented, thus the simulation was done without the metallisation.

In Fig. 12 the IV-curve for the simulated chip is plotted. Two fitted lines meet at 65V, and one can see that the chip seem to be fully depleted at a bias voltage of 100V. This is significantly higher than the 26V that we measured with the data from the clean room. One of the most obvious reasons can be the usage of simulation parameters which do not correspond with reality, as we had to skip the metallisation contact.