

# Build your own Particle Detector

Using a PIN diode for detection of charged particles

**Attention:** NEVER touch the front side of the PIN diode assembly – you will destroy it. Ask an instructor before you retrieve the diode from its box.

## Introduction

If you work with detectors, in most cases they come pre-assembled; you will probably need a power supply of some sort and a digitizer to convert the output of your detector in something your computer can digest. In some cases, you may use a pre-amplifier box and a main amplifier of some sort, sometimes with a few knobs to turn to improve the signal-to-noise ratio or adapt the amplifier output for your digitizer input. How the detector converts the particle interaction into a useful output and how this in turn changes into a recordable signal is often glossed over. However, if we want to push the limits of what we can measure, if we want to really understand what we can or cannot learn from a given signal output, or how we might be able to change things so we can get more information out, it is important to understand what allows us to extract the signal from the detector and what happens to it on its way through the ‘black boxes’ of pre- and main amplifiers.

The goal of this project is to start with a few basic components, most of which you can acquire at your neighbourhood electronics store, and turn them into a detector for charged particles. In the end we will record spectra from radioactive sources and compare them to what other detectors can achieve.

## The Components

### *PIN-Diode*

As our detector we are using a silicon PIN-diode, a semiconductor device consisting of two doped contacts. One contact is doped with acceptors – atoms with fewer valence electrons than Si such that there is a lack of electrons when the atom is put into the regular Si crystal structure (in semiconductor language this lack of electrons is referred to as an excess of holes). The other

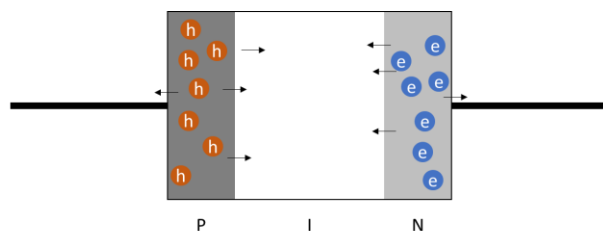


Figure 1: Schematic of PIN diode. The excess holes in the p-contact diffuse out and leave the contact negatively charge, while the electrons diffuse out of the n-contact leaving behind a positive space charge.

contact is doped with donors – atoms which have more valence electrons than Si, leading to excess electrons. These two types of doped semiconductors are referred to as *p-type* (or P, for positive due to a lack of electrons) and *n-type* (or N, for negative due to an excess of electrons). The two contacts surround an area that is undoped (or more precisely: has about the same density of donors and acceptors) called the *intrinsic* (I) region. Figure 1 shows a PIN diode

schematic. The excess holes diffuse out of the p-contact leaving a net negative charge behind while the n-contact turns positive due to the electrons diffusing out.

If we apply a voltage across the diode, the charge carriers are pushed in one direction. If a negative voltage is applied to the n-contact, electrons are pushed in, aiding their diffusion into the intrinsic region. At the same time electrons are pulled out of the p-contact, effectively producing new holes at the metal-semiconductor interface, which pushes the holes also into the intrinsic region. With electrons coming from one side and holes coming from the other side, the

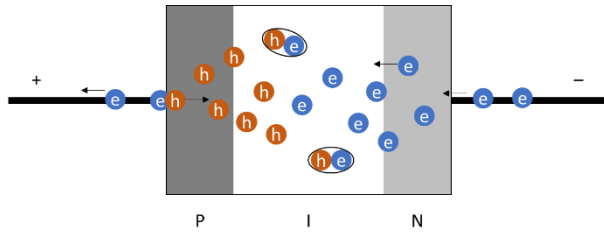


Figure 2: PIN diode biased in forward direction: electrons injected into the n-contact and holes injected into the p-contact make their way into the intrinsic region where they recombine. Thus, a current can be maintained.

charge carriers can recombine, and a current is maintained (“forward biasing”). This situation is depicted in Figure 2. If in turn the voltage is applied in the opposite direction, the electrons are pulled out of the n-contact and electrons coming into the p-contact recombine with the holes there. In this case the region without any free charge carriers is increased and once the contacts are depleted, no current can flow anymore (“reverse biasing”). In this situation the diode acts like a capacitor (see Figure 3).

However, if we find a way to lift electrons out of the valence band into the conduction band, then we restore free carriers and they will immediately drift to the charged contacts. This can happen if photons or charged particles with energies above the semiconductor bandgap enter the depleted region. Near-infrared and visible photons typically produce one electron-hole pair per photon, but particles with higher energies can produce larger numbers of electron-hole pairs. The drifting charge carriers represent a transient current. This situation is depicted in Figure 4.

For this project, we are using a large-area (1 cm<sup>2</sup>) Si PIN diode that we will have to reverse-bias.

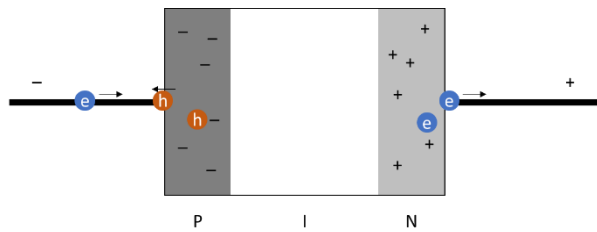


Figure 3: PIN diode in reverse bias: the intrinsic region as well as large parts of the contacts are depleted. No current can be maintained, and the diode acts effectively like a capacitor.

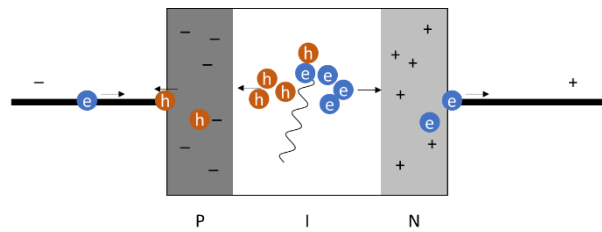


Figure 4: PIN diode in reverse bias: a particle with sufficient energy can produce one or more electron-hole pairs. The charge carriers drift to the electrodes, producing a transient current.

**ATTENTION:** The diode we are using **MUST** be handled with great care. **DO NOT TOUCH ANYTHING** on the front face of the assembly. The contact on the surface is without any protection and will be immediately destroyed. The golden patches are bond pads with invisibly thing wires to contact the surface. Those are the most vulnerable parts. The diode is one of the parts that you cannot get at a typical electronics store and it is the most expensive part of the setup.

### Operational Amplifier (op-amp)

The signal we get from the PIN diode is a transient current formed by a relatively small number of electrons. If we try to measure this current as it comes out with a standard current meter, it will not even notice that something happened. The same holds for a standard digitizer. We therefore need to convert this faint charge signal into a robust voltage signal at an amplitude that can easily be digitized. This means we need an amplifier. The basic electronic component that is usually used to build an amplifier of the type we need is an Operational Amplifier (or op-amp for short). This is in itself a fairly complex device with some 20 transistors and a dozen or so resistors, but we will ignore its internal secrets and only concentrate on its effective behaviour. An op-amp usually has two inputs and an output. The inputs are of high impedance (aka there is no appreciable current that flows if a voltage is applied on the input). The op-amp produces a voltage on the output that is proportional to the voltage difference on the two input terminals. In contrast to the inputs, the output terminal has a low impedance (aka the voltage is maintained even if a significant current is drawn).

The ratio between voltage difference on the inputs and the voltage on the output is referred to as 'open-loop gain'. This gain is usually very high, but the exact value is not well known or controllable. Therefore, an op-amp is usually integrated into a circuit that includes some type of feedback, where the effective output is controlled by the circuit and not the gain of the op-amp. The open-loop gain of the op-amp then primarily determines how fast the circuit reacts (unless that is also dictated by the circuit around it).

An op-amp is usually depicted as a triangle where the inputs that are compared enter on the base and the output comes out of the tip. Of course, the op-amp needs a power supply so it can maintain the output current. The supply voltage is not shown in most circuit diagrams, but it won't work without.

There is a near infinite number of ways an op-amp can be used in a circuit to produce whatever type of amplifier you can imagine. Figure 5 shows some typical choices for a charge and a voltage amplifier.

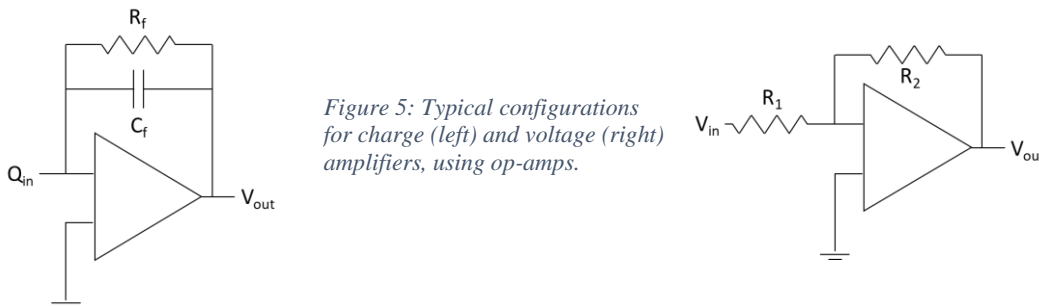


Figure 5: Typical configurations for charge (left) and voltage (right) amplifiers, using op-amps.

The op-amp we have available is packaged in a small integrated circuit (IC) unit which in fact includes two op-amps. The op-amp ICs are a couple orders of magnitude cheaper than the PIN diode but are still expensive enough that we don't want to blow up too many of them or kill them by overheating. Before you are ready to incorporate them into your circuit, please confirm that the circuit will not put them in danger.

### *Electronic components*

The rest of the electronic components we are using are resistors and capacitors. We have a good selection of these components available for you to choose from. We don't have every conceivable value, but we made sure that we cover a good range.

### *Mechanical support*

In order to put your circuit together, we provide you with a prototyping board and a soldering iron. We do have a few spare boards, and if you make a mistake, it can be corrected in most cases. The prototype board provides certain connections, but you may need to add additional connections that you can accomplish by using wire jumpers. We have wire and wire cutters available.

Building the circuit isn't sufficient for your detector to work: as indicated above, the PIN diode is able to detect visible photons, so if light shines on it, you will get a continuous current (in fact, light sensors are one of the important applications of PIN diodes) and you won't be able to detect your particles. Also, the circuit must be extremely sensitive to be able to detect the small amount of charge that is liberated by the particles to be detected. This makes it also vulnerable to environmental conditions, such as electromagnetic radiation in the radio range (Radio Frequency, or RF). Both of these problems will be tackled by placing the whole setup in a box that shields from light and RF radiation.

### *Data Acquisition*

In order to study and record the signal produced by our detector and circuit, we have a nice little device available that includes the functionality of an oscilloscope and a Multi-Channel Analyser (MCA) among many other things. The former is used to look at the quality of your signal and potentially investigate the performance of different parts of your circuit, while the latter is used to record energy spectra. The device is called Red Pitaya and is a combination of a mini-computer (comparable to a Raspberry Pi) with a Linux-based OS and an FPGA ('Field Programmable Gate Array'). The oscilloscope and MCA are realized by software applications that take advantage of the fast digitizer that is part of the FPGA. Since there is only one digitizer, they cannot run simultaneously. There are two inputs that can be configured for a 1 or 10 V input signal. There are also two outputs, but we won't use those.

### **What to do**

Your goal is to build a detector that can detect alpha particles and measure an alpha spectrum. The detector itself is the PIN diode and the small charge produced has to be amplified into a robust voltage signal. It is likely that the output from the charge amplifier you build is considerably smaller than the input range of the Red Pitaya, so you will probably need to configure a second amplifier as well. The first converts your charge signal into a voltage signal and the second then amplifies the voltage output from the first amplifier. Once done, you will test your detector with a low-intensity alpha-source. Acquire an energy spectrum. If time permits, you can assess the signal-to-noise ratio and estimate the lowest energy deposition you might be able to detect and/or assess the sensitivity to betas.

You may want to compare your detector to a similar device that is available in the lab.

Complete a report with your results / findings / conclusions.

## Things to consider

- Why are the amplifiers shown in Figure 5 charge and voltage amplifiers? What are their amplification factors?
- The energy bandgap of Si is 1.1 eV, but if a high energy particle interacts in Si, the conversion into electron-hole pairs is not very efficient. For gammas and electrons, you will get on average one electron-hole pair per 3.8 eV of deposited energy. Alpha particles deposit their energy in a different way, leading to an electron-hole pair production efficiency that is about a factor of 5 lower. Typical alpha energies are of order of a few MeV. What is the total amount of charge we can expect to observe? What amplification factors do we need to make best use of the input range ( $\pm 1$  V) of the Red Pitaya?
- In order to collect the signal, we need to apply a voltage bias. How do we prohibit the charge we want to measure from just disappearing into the voltage source that biases the detector?
- Further, how will applying a bias of several volts (or tens of volts) across the detector impact the op-amp circuit which compares input voltages to produce an output? Typically, the input to compare with is at ground.

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