The Testing of Photodiodes

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1. Introduction

The High Resolution Array (HiRA) is a charged particle detector array consisting out of 20 telescopes. It is currently being designed and built at the NSCL. Each of the telescopes will contain 2 Si-strip detectors and 4 CsI (Tl) scintillation detectors. The scintillation light produced by charged particles that are stopped in the CsI (Tl) crystals is readout by photodiodes which are attached to the back of each crystal. Photodiodes are the typical choice for the readout of CsI (Tl), because they have high quantum efficiency in the range of the CsI (Tl) scintillation spectrum and also because they are much more compact and less expensive than photo multiplier tubes.

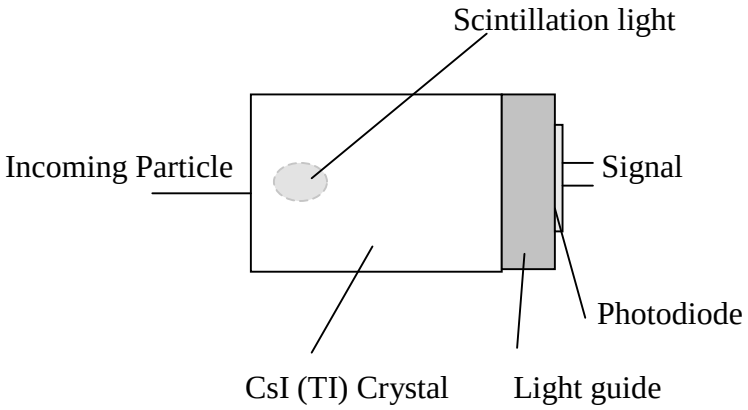


Fig 1 shows the way that the photodiode is connected

The photodiodes used here consist out of a thin layer of p-doped Silicon followed by a thick layer of n-doped Silicon. When a bias voltage is supplied the charge carriers are pulled further from the p^+ - n junction creating a layer in which there density of carriers is virtually zero. This layer is called the depletion layer and its width increases with the bias voltage until the whole n-type Silicon waver is depleted. The voltage at which the whole n-type Silicon layer is depleted is called the depletion voltage. Across the depletion layer of the photodiode a strong electrical field will be present. This electrical field will collect the electrons, produced by the interaction of photons with the Silicon, on the connector to the n-type wave creating a small current. Because the current is very small it has to be pre-amplified by a pre-amplifier located very close to the photodiode.

Photodiodes are a type of semiconductor detector normally made of silicon. Within the semiconductor, there exists an energy region with three basic parts, the valance band, the energy gap, and the conduction band. The valance band contains electrons with lower energy than those of the conduction band and is the ground state of the energy region. Electrons located in the valance band are more bound to the nucleus of the atom. The energy gap, or band gap, is a region of energy where no electron can exist. The width of this structure is determined by the lattice spacing between atoms. If the lattice is widely spaced, then the energy gap will be larger; whereas, if the lattice in narrow, then the energy gap will be more narrow. The conduction band houses electrons that have gained enough energy to “jump” the band gap. They are not as attached to the nucleus of the atom, thus they are free to move between atoms. This movement causes a current to flow through the semiconductor material. The movement of electrons can be caused by an electric field.

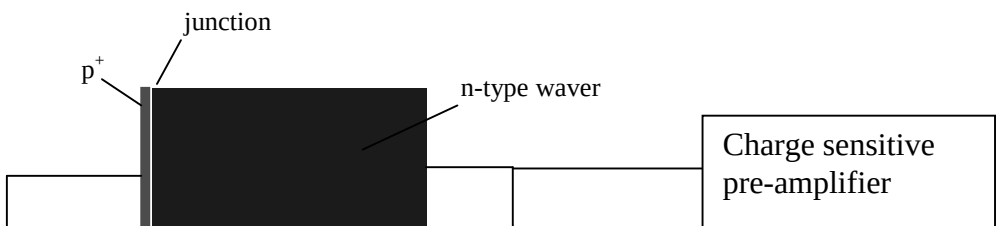
Electron-hole pairs are recombined in two ways, recombination and trapping. Recombination occurs when an electron drops from the conduction band into the valance band and fills the hole that it while emitting a photon of energy. Trapping is caused by an impurity in the

semiconductor. This impurity creates another energy level within the energy gap, known as the recombination center. Two things can occur at this recombination center: the electron can gain enough energy and move to the conduction band or the electron is annihilated by a hole that enters the recombination center. Recombination centers are unwanted because they create an area where some of the electrons are destroyed before they are detected.

The functioning of the semiconductor is dependent on the junction it contains. The most common type of junction for semiconductors is the n-p-junction. This type of junction is formed when a p-type semiconductor is interspersed in an n-type region.

Between the p and n materials lays a regions where holes and electrons recombine due to the differing concentrations on either side of the junction. Being initially neutral, this recombination causes a buildup of charge. The p region will become negative and the n region will become positive at the junction, which creates an electric field gradient that stops the diffusion of charge carriers. This causes an area of no mobile charge, known as the depletion region. . This layer is called the depletion layer and its width increases with the bias voltage until the whole n-type. The voltage at which the whole n-type Silicon layer is depleted is called the depletion voltage. Across the depletion layer of the photodiode a strong electrical field will be present. This electrical field will collect the electrons, produced by the interaction of photons with the Silicon, on the connector to the n-type wave creating a small current. Because the current is very small it has to be pre-amplified by a pre-amplifier located very close to the photodiode.

If a reverse bias is applied to a semiconductor, it has been found that the noise is decreased by the attraction of majority charge carriers to their respective side of the junction, holes to the p-type region and electrons to the n-type region; however, the effects of the reverse bias voltage are



limited by the resistance of the photodiode. At a certain voltage, the junction will break down and begin conducting.

In order to achieve a high energy resolution for particles that are stopped in the CsI (Tl) crystal the photodiode readout should have a low overall electronic noise level. One of the most important sources of noise is the photodiode it self, as this noise gets amplified by the pre-amplifier and (although in a lesser manner) by the shaping amplifier. The noise produced by the photodiode consists out of several contributions: Schottky-noise, contact-noise, and pickup-noise. Shielding the photodiode in a Faraday-cage can minimize the last contribution. Cooling the Photodiode can in principle reduce Schottky-noise as it reduces the number of charge carriers produced in the depletion zone by thermal excitations, which give rise to the leakage current. Cooling of the photodiodes is however not possible in a practical design of the HiRA. The contact-noise contribution is harder to address as it can vary strongly between each individual photodiode.

The charge-sensitive preamplifier will amplify the noise from the photodiode with a multiplication factor that is linearly dependent on the capacitance of the photodiode. The idea is thus to use a photodiode with a small capacitance. The following relation gives the capacitance $\boldsymbol{C}$ of a photodiode,

$$\boldsymbol{C} = \boldsymbol{\varepsilon} \cdot \frac{\boldsymbol{A}}{\boldsymbol{d}},$$

Where $\boldsymbol{\varepsilon}$ is the dielectric constant of Si, $\boldsymbol{A}$ is the active area of the photodiode and $\boldsymbol{d}$ is the thickness of the depletion layer. The size of the active area of the photodiode cannot be decreased too much, because this will decrease the amount of scintillation light that is collected from the crystal. One actually might want to increase the area instead of decreasing it. The capacitance can, however, be

decreased by increasing the thickness of the depletion layer. Choosing a thicker photodiode and using a higher reverse bias voltage can achieve this.

To see if a thicker photodiode will indeed perform better than the thinner photodiode, three photodiodes were tested. The photodiodes are listed in table 1, two photodiodes with the same Active area but with different thickness of the depletion layer were compared to each other.
The third photodiode has a larger area; this diode has not been compared in full, as its price is too high. In the consideration which photodiode to use the cost will also play an important role.

Photo diode Number	Manufacturer	Thickness of depletion layer	Active Area (L x W cm^2)	Cost
1	Hammamatsu	300	1.8 x 1.8	~$100
2	Hammamatsu	500	1.8 x 1.8	~$200
3	Hammamatsu	500	2.8 x 2.8	~$400

Table 1: list of photodiodes that have been compared to each other

The test

In order to make sure that the photodiode have in deed different capacitances and to find the full depletion bias voltage, the capacitance of each photodiode has been measured as a function of the bias voltage using the setup show in figure 2.

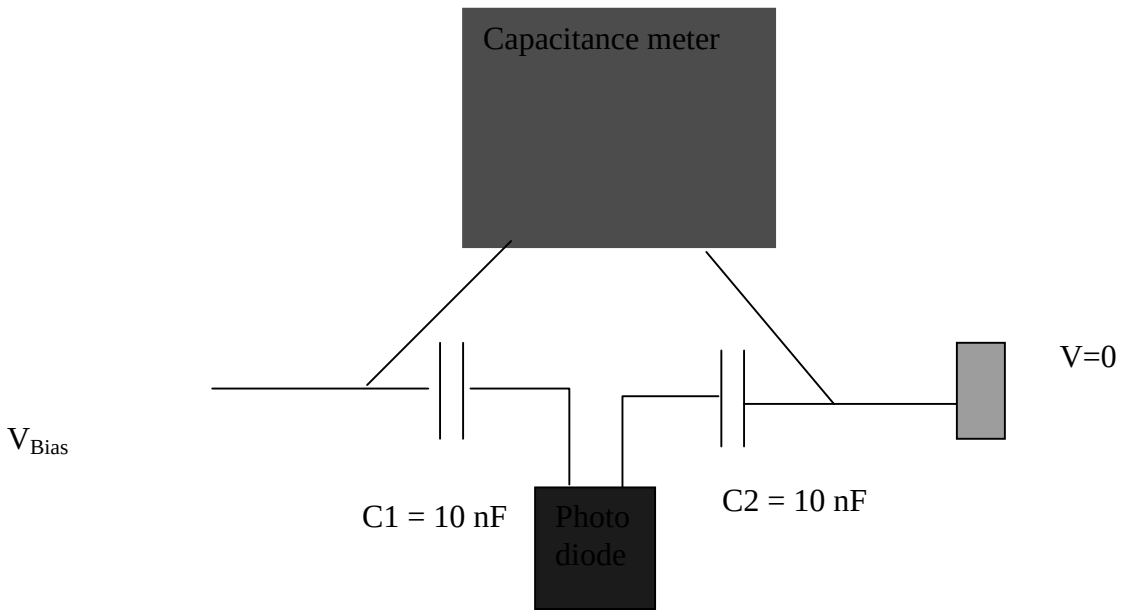


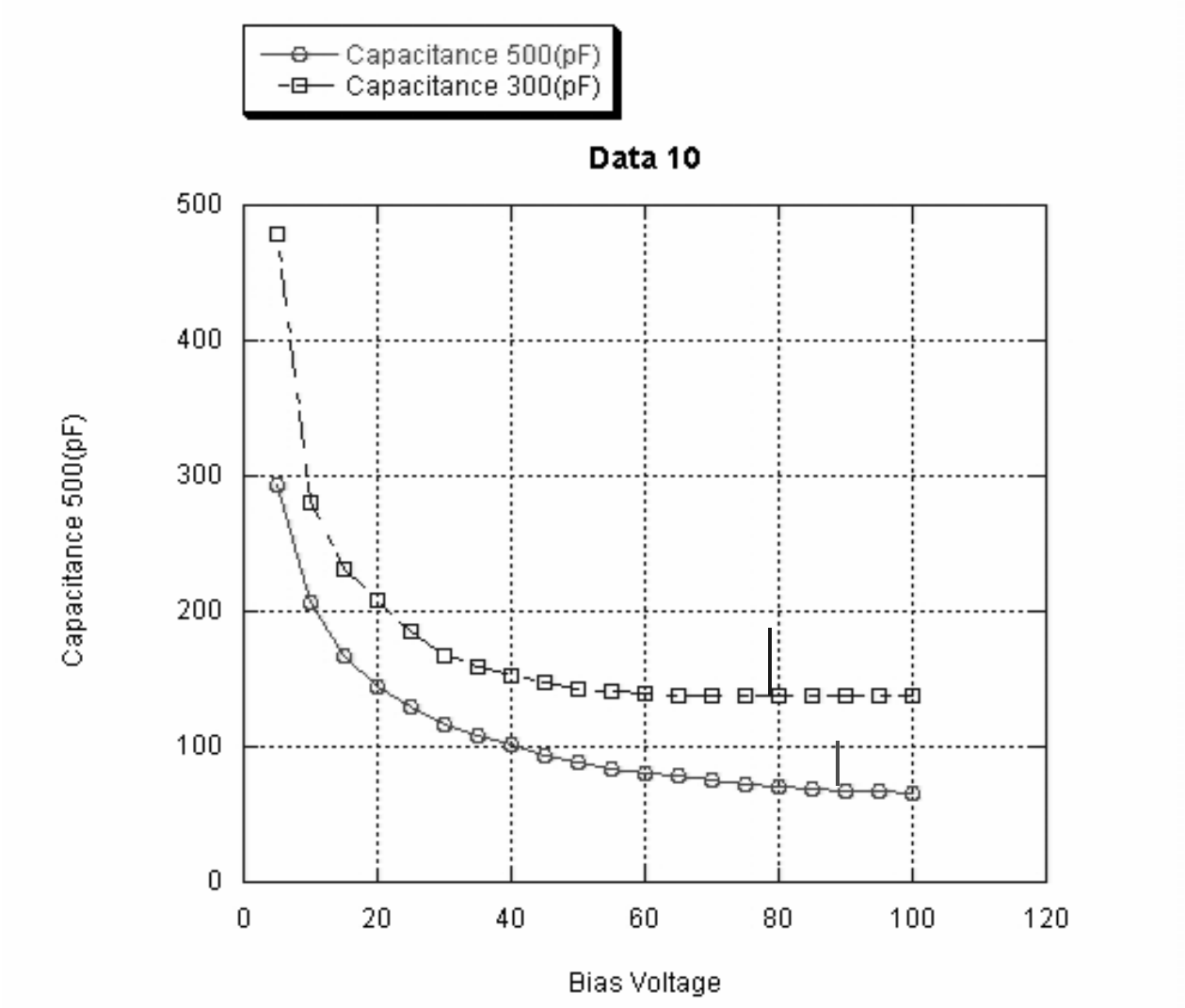
Figure 1: The setup for measuring the capacitance of the photodiodes

The capacitors C1 and C2 protect the photodiode from large currents when biasing the photodiode the measured capacitance C_m is given by,

$$\frac{1}{C_m} = \frac{1}{C_{diode}} + \frac{1}{C1} + \frac{1}{C2}$$

The full-depletion voltage is that bias voltage at which the capacitance does not decrease any more with increasing bias voltage. Figure 2 shows the dependence of $\boldsymbol{C_{diode}}$ as a function of the bias voltage. In the figure the full-depletion voltages of the 300μm and 500μm photodiodes with the active area of 1.8x1.8cm^2 photodiodes have been indicated.

Figure 2:



In order to compare the noise from the different photodiode the full width half maximum (FWHM) of a pulser was measured in the setup shown in figure 3. The setup consists of a charge sensitive preamplifier, a bias voltage supply, a shaping amplifier and a multi channel analyzer. In

order to shield the photodiode and pre-amplifier from pickup-noise they were placed inside a vacuum chamber.

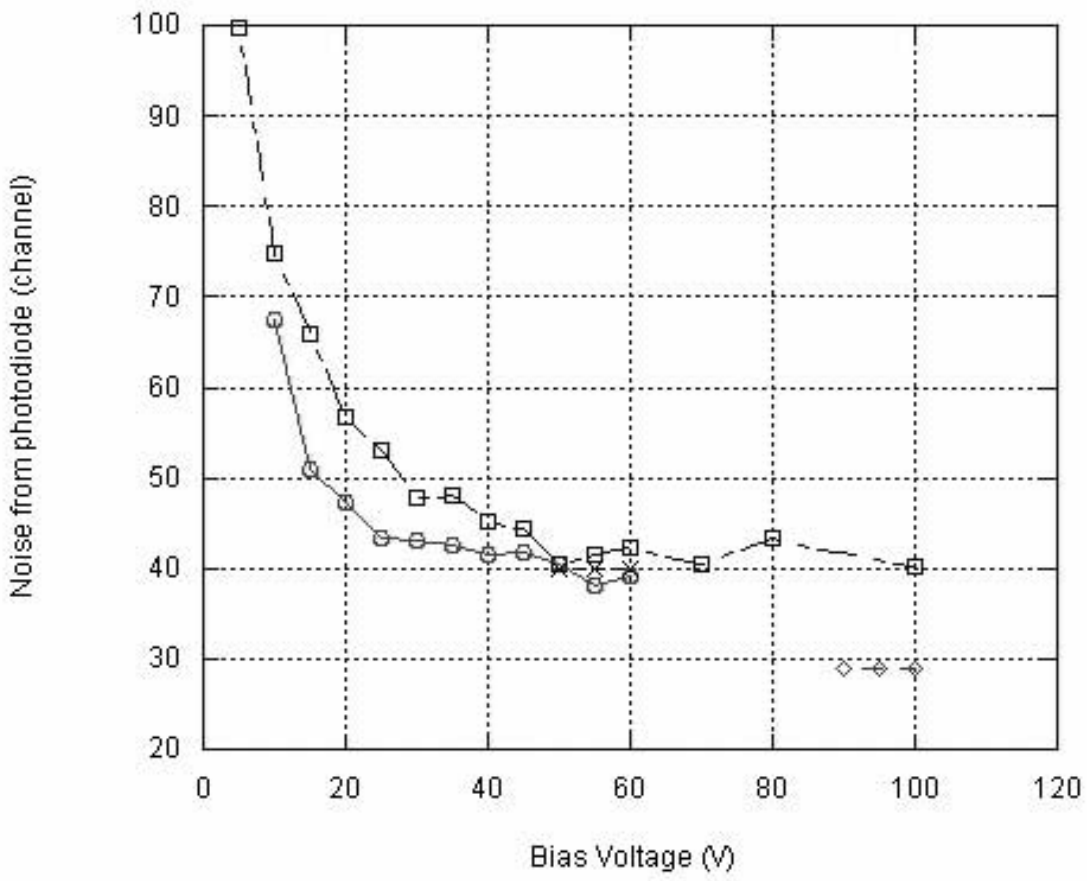
If there were no noise, the FWHM of the pulser would appear as a straight spike on the readout; however, since there is noise, the FWHM is a peak. The more noise there is in the system, the wider the peak will become. This peak is readout via a computer. The FWHM is directly correlated to the noise of the system.

The FWHM of the pulser has been measured for each photodiode using a series of the bias voltages ranging from 10V to 80V. To measure the noise contribution from other parts of the electronics, the FHWM of the pulser has also been measured without the photodiode attached. We will refer to this as the base line.

In figure 4 the FWHM of the pulser is shown as function of the bias voltage for photodiodes 1 and 2 and also the base line is indicated. The figure shows that the noise decreases with the bias voltage until a certain level. The noises measured with both photodiodes at their respective full-depletion voltages do not show a large difference. We expected a big difference, as their capacitances are a factor 2 different.

One explanation might be that the size of the Schottky noise increases with the size of the depletion layer, because it has some volume dependency. If this is the case one might be able to reduce the noise by lowering the temperature of the photodiode. Figure 5 shows the FWHM of the pulser measured with photodiode 2 at 25deg C and at 4 degC as a function of the bias voltage. The noise seems to be slightly smaller in when the photodiode is cold.

Fig 4: The FWHM of the pulser as a function of the bias voltage. The red graph represents the noise of the 500µm photodiode and the blue line represents the 300µm photodiode.



Conclusions

- At room temperature there is no difference between 300 and 500 micron thick photodiodes
- Cooling the photodiode will improve its performance
- No reasons to buy more expensive photodiode for the HiRA

Reference:

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