GRIDS2024
Graduate Instrumentation and Detector School

Characterization of Silicon Photo-Multipliers (SiPMs)

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1) Introduction:

In this laboratory, you will gain experience in understanding the intrinsic properties of Silicon-based photomultipliers (SiPMs), as well as how to set up and operate them in different modes.

SiPMs are solid-state devices designed to precisely measure single instances of light. In contrast to the widely used Photomultiplier Tubes (PMTs), SiPMs are low-voltage powered, optimal for operation at cryogenic temperatures, and have low radioactivity levels with high gain stability over time in operational conditions.

SiPMs consist of an array of tightly packaged Single Photon Avalanche Diodes (SPADs) operated above breakdown voltage, to generate Geiger-mode avalanches. Each SiPM SPAD is a reversely biased p-n junction, operated above breakdown, with a quenching resistor placed on each cell to recover from the avalanche. A schematic representation of the junction with the avalanche region is shown in Fig. 1. In this configuration, a photogenerated carrier (electron or hole) entering the depletion layer may trigger an avalanche, and will experience a large change in momentum (field-induced acceleration). The previous step leads to multiplication via radiative processes, the strength of which is referred to as the gain. Average SiPMs have a gain of the order of 105 secondary electrons produced per single photo-electron. Because of their intrinsic structure and design, SiPMs are outstanding photo-counter with well separated single to multiple photo-induced electron counting. The output of a SiPM is a chronological superposition of current pulses, and it can be parameterized by three time constants as follows:

$$V(t) = A\cdot\left[\left(\frac{1-k}{\tau_S}\right)\cdot\left(e^{-t/(\tau_S+\tau_r)} - e^{-t/\tau_r}\right) + \left(\frac{k}{\tau_L}\right)\cdot\left(e^{-t/(\tau_L+\tau_r)} - e^{-t/\tau_r}\right)\right]$$

Where τ_R is the pulse rise time, A is the pulse area, t_0 is the pulse time, and τ_s and τ_L are the short and long pulse fall time constants, respectively. k is the relative contribution of the two fall time components in the SiPM pulse shape: $0 \leq k \leq 1$. It should be noted that the short-time constant is proportional to the total resistance of the device and its parasitic capacitance, while the long-time constant is proportional to the strength of the quenching resistor.

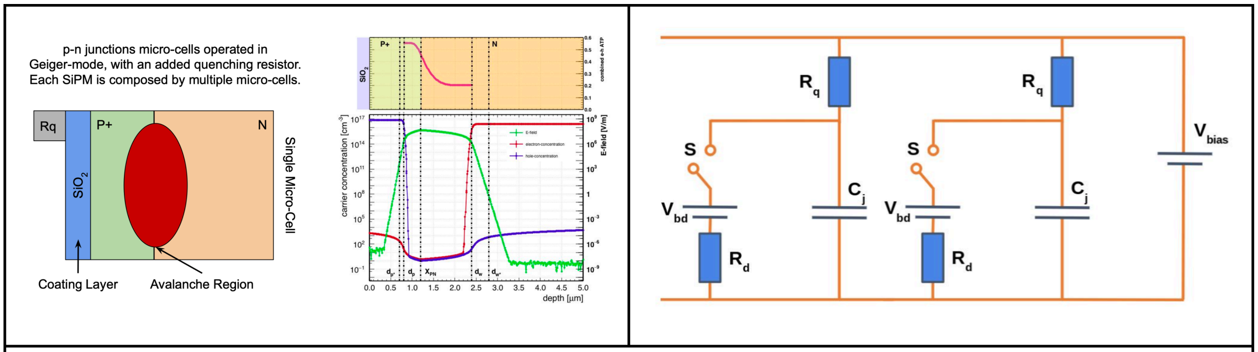

Fig. 1) Left: schematic representation of the p-on-n SiPM. Note that on the surface the device always features an oxidization layer (SiO2) as bare silicon has a very low Lenord-Jones surface potential. The figure also shows the relative strength of the E-field in the avalanche region with respect to the two doped portions. Right: electronics schematic of how microcells (SPAD) are combined in series to form a SiPM.

Like any other device, SiPMs have different noise effects. The most common is dark noise, which occurs when an avalanche is triggered in the absence of light striking the device, with an electron that is thermionically kicked out from the Silicon lattice. The rate of dark noise is proportional to the voltage and temperature of the device, and in most devices, the rate drops about one order of magnitude for every 20 degrees celsius. Dark noise pulses are indistinguishable from those due to photons and can only be suppressed via cooling or trigger settings. Another noise effect arises when a primary discharge can trigger a secondary discharge in neighbouring microcells. This is referred to as crosstalk, and the different possible configurations are shown in Fig. 2. Crosstalk is a very prompt event (few hundred ns), that depends primarily on the voltage settings, and can bias photo-counting by adding extra charge.

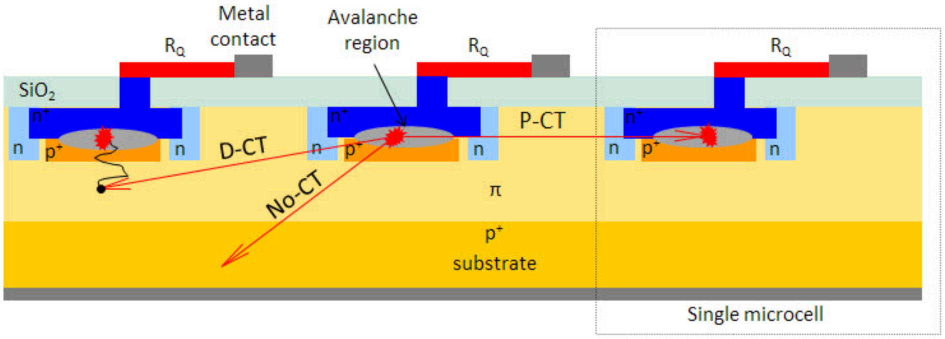

Fig. 2) This skematics illustrates the different mechanisms for crosstalk noise. Prompt (P-CT), delayed (D-CT), and no (No-CT) crosstalk.

SiPMs can be operated in two modes, current (or continuous) mode or pulse counting mode. In continuous mode, a bias is applied to the device and a pico ammeter is used to constantly read out the current from the unit. In pulse counting mode instead, the biased SiPM output is amplified and digitized to visualize and measure avalanche-induced charge signals.

2) Experimental Setup:

2.1) SiPMs

For this laboratory, you will be taking data and characterizing the performance of two devices designed by different manufacturers to be primarily sensitive to light in the VUV range. Both devices, mounted on a PCB with a triax connector, are shown in Fig. 3.

The first device is produced by Hamamatsu, and it's referred to as VUV4. Packaged in white ceramic, this device is 3.5x3.5 mm in surface area and features microcells with a pitch of 50 microns. The VUV4 also features tungsten optical trenches between microcells to reduce the effect of crosstalk.

The second device is produced by the Fondazione Bruno Kessler (FBK), and it's referred to as FBK-VUV-HD3. This is a bare chip that was directly wire-bonded onto the connector PCB, with a surface area of 6x6 mm (larger than the VUV4). The microcells also have a larger pitch of 75 micrometres each. FBK reduces noise with a different technique than Hamamatsu, they use smaller optical trenches but their Silicon has a higher level of doping.

Fig. 3) Image of the two Silicon-Photomultipliers to be used in this laboratory. The unit on the left is the FBK-VUV-HD3, while the device on the right is the Hamamatsu VUV4. Both are wired-bonded onto a structure PCB with a triax connector for bias and signal.

2.2) Electronics

All electronics needed to operate the devices in either pulse counting mode or continuous mode are provided in this laboratory, with the full setup shown in Fig. 4.

- SiPM Pulse Charge Amplifier - TRIUMF Custom Design
  This amplifier features an OP amp that increases the charge signal from an avalanche to reach an S/N ratio > 4. This unit requires +/-12 V input for the OP-amp as well as a biased feed for the SiPM.
- Picoammeter - Keithley 6487
  This picoammeter function as a dual current readout and voltage supply, enabling it to perform IV measurements without the need for a secondary bias supply.
- TRIAX split box - TRIUMF Custom Design
  Because the signal from the SiPM is carried through triax cables, this box is needed to split the voltage and current feeds into the picoammeter.
- SiPM Bias Voltage Supply - Keysight E3649A
  This unit will be used to provide a bias voltage to the SiPM when running in pulse counting mode. The supply connects straight to the OP-amp box, which then feeds the voltage through the triax cable to the desired SiPM.
- OP-Amp Power Supply - Aglient E3631A
  This unit, similar to the one above, is also used for pulse-counting mode, however, it is to provide + and - 12 V to the OP-amp to function. Note that the OPamp is very sensitive to current spikes.

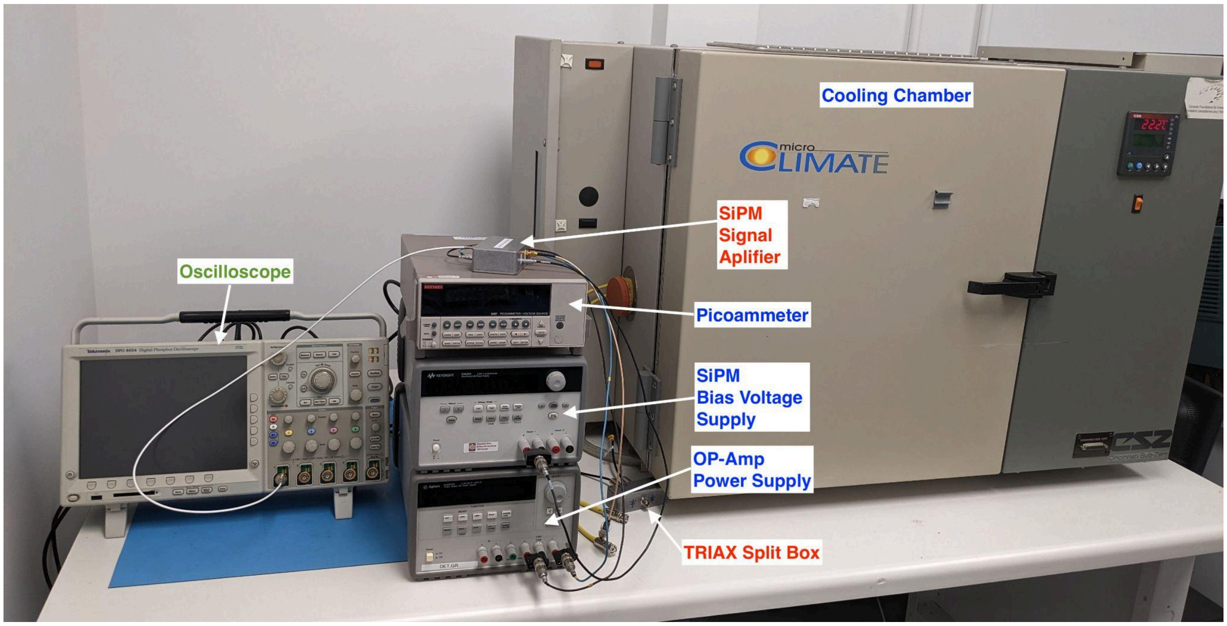

Fig. 4) Image of the full set of equipment available for the SiPM laboratory. Highlighted are the position and cabling for the oscilloscope, picoammeter, bias supplies, split box and OP-amp.

2.3) Cooling Chamber

The cooling chamber serves two functions. First, it acts as a black box for the SiPMs, to make sure that we can run them in the dark with no background light striking the surface during studies and characterization. Any stray light would skew any measurement and depending on the size of the light leak might even damage the SiPMs. Secondly, the chamber can provide cooling to the unit to perform measurements at different temperatures. The operation instructions for the microCLIMATE unit can be found in the cabinet underneath the electronics, while an online digital copy can be found here. Instructions should be followed very closely when operating the unit, and the demonstrator should be consulted if it is the first time you are cooling the chamber. Note that the chamber should not be used below -40 C and that it might take up to 3 hours to reach the desired temperature.

3) Operation:

Note, if in doubt always ask an instructor first. Especially with the voltage supplies, do not apply voltage on any component until you are sure that everything is properly connected and that the SiPM are dark. Please also remember that you are working in a functioning lab, so be respectful to the people doing research around you.

3.1) Continuous Mode

To perform an IV measurement of the devices the following steps should be followed:

1. Make sure the SiPMs inside the cooling chamber are connected to their respective triax cables, and that the unit is fully closed and light leak free.
2. Outside of the cooling chamber, plug the triax cable of the SiPM you want to characterize into the split box. Note that if you are switching between devices the picoammeter should be turned off when completing this step. The connection from the split box to the picoammeter is already done, do not change the configuration.
3. Ensure that all the cable connections in the back of the picoammeter are properly done, then turn the picoammeter (back) on.
4. Using the buttons in the v-source section, set the voltage to 1 V and click the OPER button to let voltage flow into the device. If the current overflows, it means that the SiPM was set up in the wrong bias configuration (reverse vs forward). If the current readout on the unit is of the order of a few nA you can proceed with the next step. Please perform this step every time you plug in a new device.
5. Bring the voltage to 25 V and click the OPER button to let voltage flow into the device. Note that the OPER button should be turned off everytime you edit the voltage settings.
6. Increase the voltage in steps of 2 volts and record the current reading until you see the transition from liner mode to Geiger mode (current should spike from nA to uA).
7. After you determine roughly where your breakdown voltage is, lower the voltage to about 2 V below that and re-perform the scan in increments of 0.5 V instead of 2 V. You can

repeat this step multiple times with finer and finer steps until you are satisfied with your breakdown voltage measurement.

8. Lastly, make sure the OPER button is off and then power off the whole unit.

3.2) Pulse Counting Mode

To perform pulse counting measurements the following steps should be followed:

1. Make sure the SiPMs inside the cooling chamber are connected to their respective triax cables, and that the unit is fully closed and light leak free.
2. Make sure all power supplies are off, this step is necessary even when switching between SiPM signals to prevent burnout on the devices and amplifier.
3. Connect the OP-Amp power supply (Agilent) to the amplifier box via the labelled OP-amp LEMO connectors. Make sure the polarity is correct, this is crucial.
4. Connect the bias voltage power supply (Keysight) to the amplifier box. Similar to step 3, make sure you have the correct polarity, as this could damage the SiPM.
5. Connect triax to traix-to-BNC adaptor. Make sure it’s far from the amplifier box or you will pick up induced noise.
6. Connect the amplifier output to the oscilloscope. You want the oscilloscope on as you power the different components up to make sure everything is ok.
7. Start by powering up the OP-amp. Turn on the Aglient power supply and click the RECALL button twice to select the preset settings for +12V and -12V. Click the ON/OFF button to let the voltage flow to the amplifier and check the current readout. The Agilent current readout should be 15 mA for the -12V channel and 35 mA for the +12 V channel. If the currents differ by more than 2 mA power off the unit and consult with the demonstrator.
8. Slowly (2 V per sec) increase the SiPM bias voltage via the Keysight power supply. Raise the voltage until you reach the breakdown voltage you measured in continuous mode for the specific device.
9. Check on the oscilloscope that you see pulses. If you don’t see anything above baseline, power off both power supplies and check the setup again. Remember to make sure the trigger level is correctly set around -10 mA.
10. If step 9 is cleared, you can proceed by increasing the SiPM bias voltage as desired. Please make sure not to exceed 8 V above the breakdown voltage. This is to ensure that we don’t oversaturate the devices and potentially reduce their performance.
11. Use the oscilloscope or the RedPytia to collect data in pulse counting mode as needed.
12. When your measurement is completed, power off the supplies. Note, before powering off the bias voltage supply, dial it back to 20 V.

4) Possible Measurements:

The main goal of this laboratory is to learn how SiPMs work, are operated, and how their physical properties shape their output. With different characteristics based on their design, SiPMs can be used in a variety of applications. Please use the list below more as an option list, and feel free to pursue whatever measurement might interest you the most.

- **[Continuous Mode]** Measure the overall current throughput as a function of bias voltage (IV-Curve) to understand the basic response of different devices. This measurement could be repeated as a function of device temperature.
- **[Pulse Counting Mode]** Characterize single photo-electron (1PE) pulses, and compare the peak height for 1PE, 2PE, and 3PE pulses for different bias voltage set points. This measurement could be repeated as a function of device temperature.
- **[Pulse Counting Mode]** Estimate the thermionic dark noise rate, and investigate the crosstalk noise by comparing the first 200 ns from the pre and post-trigger window. This measurement could be repeated as a function of device temperature.

Based on your measurements, of the SiPMs provided, which one would be better suited for each fo the following applications:

1. A scintillation rare-decay experiment that relies on photo-counting for calorimetry, which requires a S/N>10 for 1PE at 4 V above the breakdown voltage point.
2. An experiment designed to monitor intensity deviation from a constant light source, where the primary requirement is to minimize power consumption.

5) Useful Readings:

- G. Gallina, et. al, **Characterization of SiPM Avalanche Triggering Probabilities -** in *IEEE Transactions on Electron Devices*, vol. 66, no. 10, pp. 4228-4234, Oct. 2019, doi: 10.1109/TED.2019.2935690.

- G. Gallina et. al, **Characterization of the Hamamatsu VUV4 MPPCs for nEXO**, Nucl. Instrum. Meth. A, 940, 371--379, 2019