Laboratory Exercise

Characterization of Silicon Photomultipliers

Tutors

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Place

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Abstract

This laboratory session provides an introduction to the technology of Silicon Photomultipliers (SiPM). We use a measurement setup for the characterization of single SiPM assemblies. Basic properties such as the value of the quenching resistors, the breakdown voltage, the noise rate, the cross talk and the gain are extracted.

Silicon Photomultiplier Detectors

The detectors used in this experiment are photon counters consisting of arrays of avalanche photodiodes (**APDs**) operated in Geiger mode, called Silicon Photomultiplier (**SiPM**) or Multi-Pixel Photon Counter (**MPPC**). Such devices replace conventional Photo Multiplier Tubes (PMT) for Medical Imaging applications, as for example Positron Emission Tomography (PET). They are also increasingly used in High-Energy Physics applications, such as the readout of scintillators or the detection of Cherenkov light.

Figure 1 shows a photo of a SiPM. The active area is 1 mm x 1 mm and consists of 400 APDs. Figure 2 shows a schematic representation of an individual APD. A high positive voltage is applied to the *n-p junction* at the backside of the photo diode. In this *reverse bias* configuration, the bulk of the device becomes depleted of free charge carriers and a high electric field is formed. A schematic representation of the equivalent circuit of a SiPM array is shown in Figure 3 (left). Each APD is connected through an individual *quenching resistor* $\mathbf{R_Q}$ to a common readout. The APD array is reverse biased with a voltage above the breakdown voltage ($\mathbf{V_{BIAS}>V_B}$). In this state a single photon entering one of the APDs can, through the photo effect, create an electron-hole pair that is accelerated in the high electric field of the avalanche layer, inducing an ionization avalanche. The resulting current through the quenching resistor reduces the voltage until it falls below the breakdown voltage and the avalanche stops. The current at the output (Figure 3 (right)) therefore consists of a fast spike (<1 ns) followed by a decay with a time constant

$$\tau=R_Q*C_D. \qquad (1)$$

$\mathbf{C_d}$ is the capacitance of the avalanche volume inside the APD. The signals of all APDs are readout together, such that the detected charge is proportional to the number of primary photoelectrons. The dynamic range of this measurement is limited by saturation due to the limited number of APDs.

The photon detection efficiency **PDE** of a SiPM is proportional to the quantum efficiency **QE(λ)** for photons of a given wavelength λ to create a primary photoelectron, to the efficiency for creating an avalanche $\boldsymbol{\varepsilon_{aval}}$, and to the geometric acceptance ε_{geom} determined by the fill factor of the SiPM array. Typical PDEs for SiPMs reach about 20% for blue light.

The **gain** of the SiPM is given as the charge created per primary photoelectron:

$$G=Q/e=(V_{BIAS}-V_{BD})*C_D/e. \quad (2)$$

Typical gain values are in the range from 10^5 to 10^6. Both gain and breakdown voltage change with temperature. An increased temperature leads to increased thermal vibrations in the silicon lattice, reducing the free path length of the accelerated charges. The breakdown voltage therefore increases with increasing temperature (few tens of mV/K), while the gain for a given overvoltage decreases (few %/K).

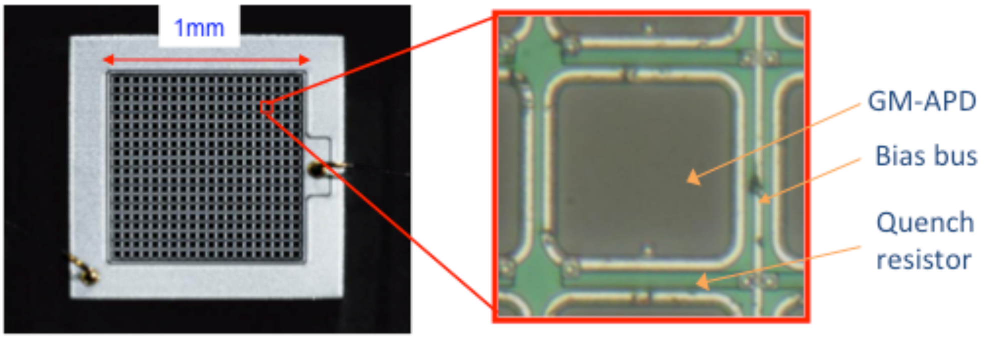

Figure 1: Photograph of a SiPM with 400 APDs

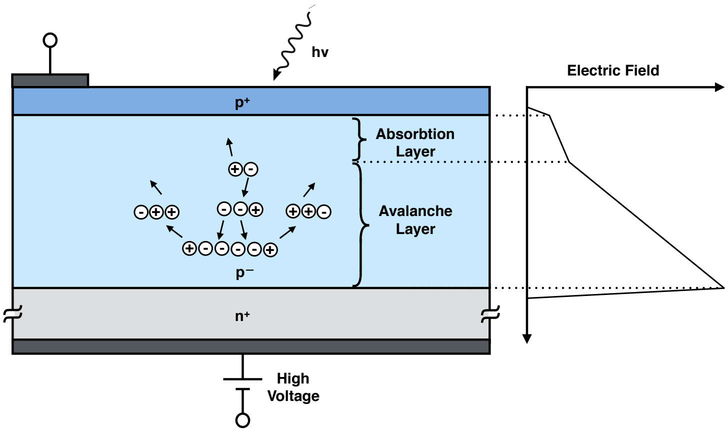

Figure 2: APD schematic

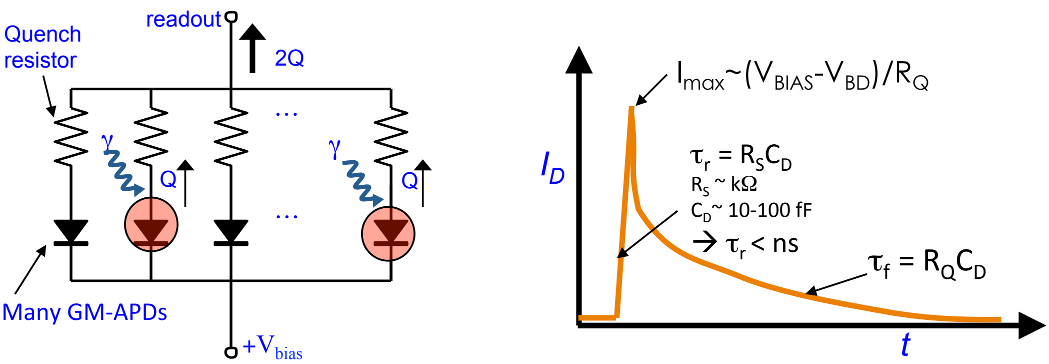

Figure 3: SiPM schematic (left) and current pulse initiated by an avalanche in an APD (right)

Besides photons or other particles traversing the APDs, also thermal/tunneling charge carrier generation can trigger an avalanche. The signal of such **noise pulses** is identical to the one created by a single photoelectron. The rate of noise pulses can reach a few MHz and increases with temperature.

Optical **cross talk** occurs when photons created in the avalanche initiate another avalanche in a neighboring cell, leading to an observed pulse corresponding to two or more photoelectrons. Cross talk occurs typically for about 10% of all pulses.

After pulses occur when ionization charges trapped in impurities of the silicon lattice get released with a delay of up to several hundreds of nanoseconds, initiating another avalanche. Depending on the delay they either lead to distorted pulses or additional pulses. Typically, a few percent of all avalanches lead to after pulses.

Measurement setup

A Hamamatsu S10943-8584 **SiPM** is used for this experiment. It consists of 400 APDs in an area of 1 mm x 1 mm. The recommended operation bias voltage at a temperature of 25 °C is 71.5 V. The temperature dependence of the breakdown voltage is approximately 55 mV/K.

Figure 4 shows a photo of the **test box** used for the experiment. An external **LED pulser** is used to create photons that are detected by the SiPM connected to an amplifier circuit.

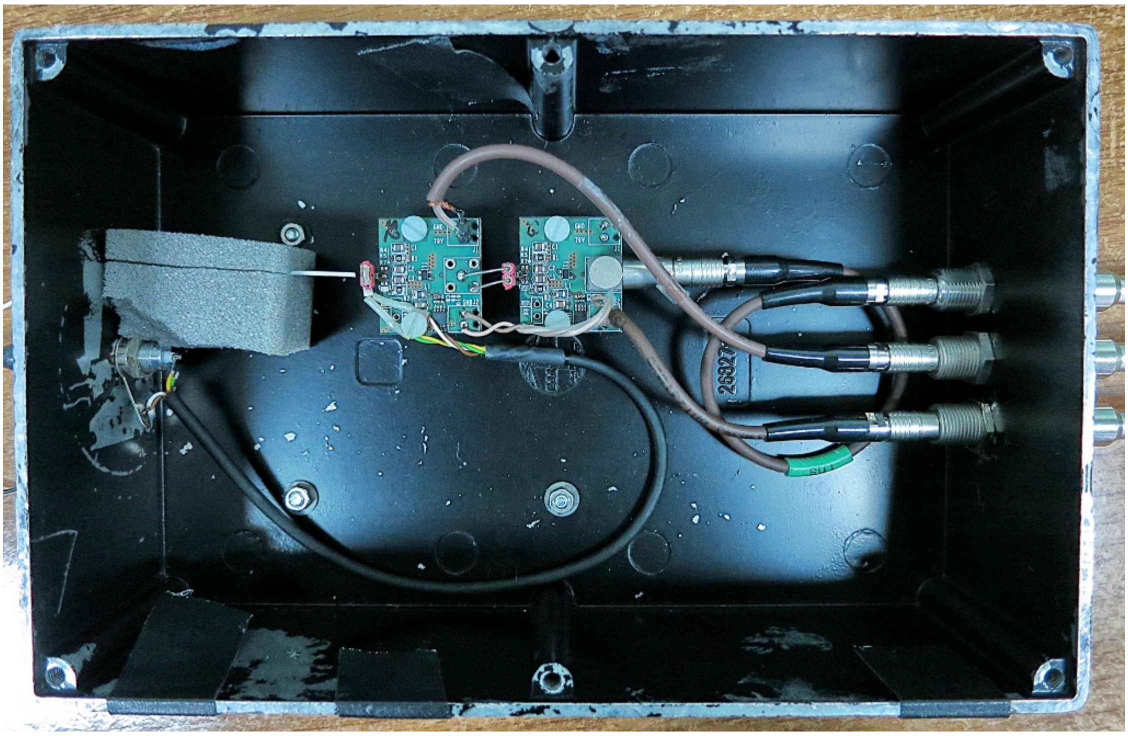

Figure 4: Measurement box with amplifier boards

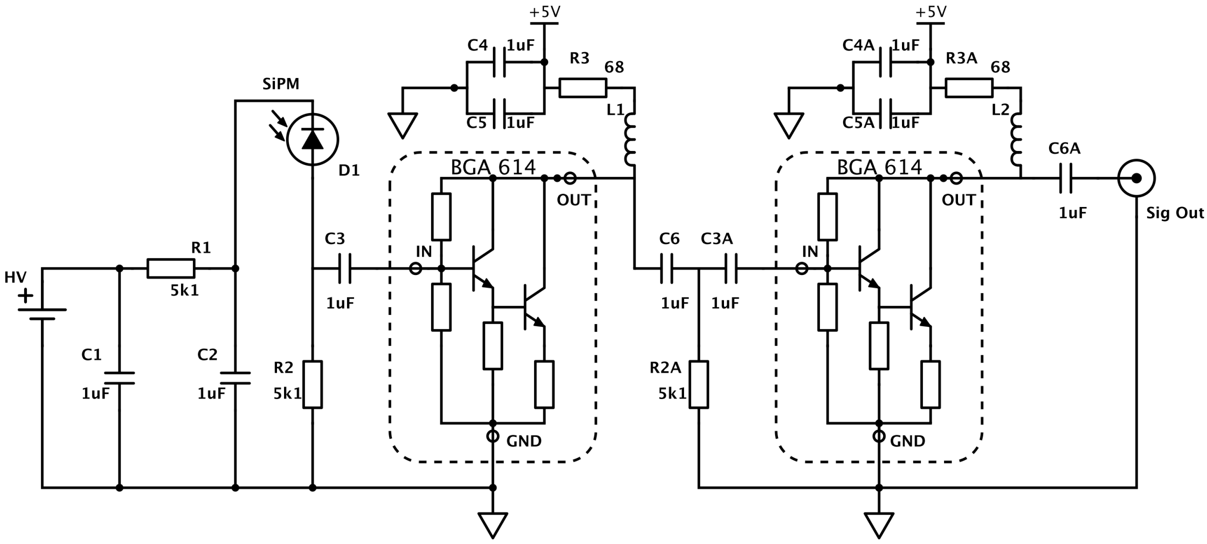

Figure 5: SiPM biasing and readout circuit

The SiPM is mounted on a PCB containing the **biasing** circuit and a one-stage **amplifier**. The amplifier converts the current signal from the SiPM to a voltage signal. It is based on a BGA614 amplifier with a fixed gain of 9. The amplifier output is connected to another amplifier of the same type on a separate PCB. Figure 5 shows the schematic of the biasing circuit and the two amplification stages. A **PT 1000** temperature sensor is used to monitor the temperature close to the SiPM.

The sensitive side of the SiPM faces an optical fiber coupled to an external **LED pulser** providing very short (~ns) light pulses of low intensity. Figure 6 shows a photo and a simplified schematics of the LED pulser. The fast switch S1 is implemented with a transistor. Its base is connected to an external trigger. The resistor R1 acts as a quenching resistor for the LED. When the switch is closed, the LED gets powered through the capacitor C1 and produces light until the voltage at the output of R1 drops below the threshold voltage of the LED (~1.5 V). The light intensity is regulated with the bias voltage V_{LED}.

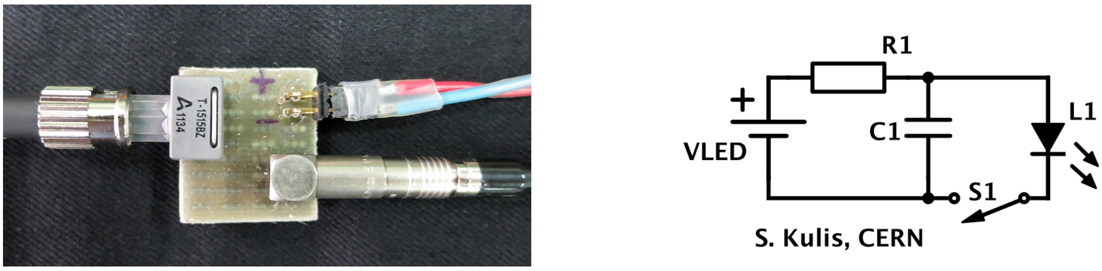

Figure 6: Photo (left) and simplified schematics (right) of the LED pulser

The output of the second amplifier stage is connected to a 500 MHz Picoscope 6404D **oscilloscope** used for the data acquisition. It also includes a **signal-generator** providing the trigger both for the LED pulser and for the oscilloscope readout. The oscilloscope is controlled by a laptop via a USB connection. The data from the oscilloscope is displayed and analyzed with a LabVIEW program.

The amplifier and the LED pulser are powered by an external Gossen 33K7 **Low-voltage power supply**. A Keithley 2410 **HV source meter** provides the high voltage for the SiPM and measures the current through the SiPM. A Fluke 45 **multimeter** is used to measure the resistance of the PT 1000 temperature probe.

Measurement 1: Value of the quenching resistors

In this exercise we determine the value of the quenching resistors through a measurement of the forward-bias current characteristic.

- Connect the HV source to the measurement box.
- Take current measurements in small steps from 0 to approximately -2 V and record them in the provided spreadsheet.
- Make a plot of the current versus voltage. Extract the resistance from a fit to the linear part of the curve.
- The amplifier board contains additional series resistors. Find them in the schematic (Figure 5). *[Optional: Confirm their values with a resistance measurement, after removing the SiPM.]* Calculate the average value of the quenching resistors, Rq, taking into account the series resistors on the amplifier board and the total number of APDs.

Measurement 2: Noise rate and cross talk

In this exercise we measure the noise rate of the device and determine the fraction of pulses with cross talk.

- Connect the low-voltage (+5 V) and high-voltage inputs of the box to the respective devices. Connect the signal output to input A of the oscilloscope.
- Measure the temperature at the SiPM through the PT 1000 resistance. Wait until it stabilizes. Note the temperature in the provided spreadsheet.
- Use the Labview software to control the oscilloscope. Turn on channel A (+-100 mV, 50 Ohm). Trigger on channel A, falling edge, and set the trigger level to be within the noise.
- Set the high voltage initially to 68 V and increase it in steps of 1 V, until the signal from thermal noise appears on the oscilloscope screen. Now set the high voltage to the recommended operating voltage of 71.5 V. Set the trigger to rising edge and a level of approximately 20 mV, which should be somewhat outside the noise fluctuations.
- Unplug the cable used for the temperature measurement and confirm that this reduces the amplitude of the noise fluctuations.
- Set the time window of the acquisition (post trigger) to 1 ms.
- A peak detection algorithm is used to count the number of noise peaks in the acquisition window. The number of peaks above the thresholds for >=1 photoelectron pulses and >=2 photoelectron pulses are displayed in the box below the oscilloscope. Check and if necessary adjust the two trigger thresholds for >=1 photoelectron pulses and >=2 photoelectron pulses. Adjust the acquisition window if necessary.
- Note the values for >=1 and >=2 photoelectron pulses in the spreadsheet.
- [Optional: Repeat the measurement for decreased and increased bias voltages (-0.5 V, +0.5 V, +1.0 V). Check the temperature before each measurement. Adjust the trigger thresholds depending on the observed signal levels. Plot the noise rate as function of operation voltage.]

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Measurement 3: Gain, capacitance and breakdown voltage

In this exercise we use the LED pulser to create photons entering the SiPM. We determine the gain, capacitance and breakdown voltage of the device by an analysis of the pulse integrals for different operation voltages. Finally, we estimate the signal fall time and the depth of the avalanche region inside the APDs.

- Use the same connections and nominal operation voltage setting of 71.5 V as for the previous measurement. In addition, connect the signal-generator output of the oscilloscope to input channel B of the oscilloscope and extend this signal to the trigger input of the box.
- Use 100 kHz square pulses, with an amplitude setting of 4 V. Turn on channel B (±1 V, 1 MOhm).
- Trigger on channel B at a level of 0 V, falling edge. Set the post-trigger time window to 100 ns and the pre-trigger time window to 50 ns. Adjust the LED pulse intensity by changing the bias voltage of the LED pulser in a range from approximately 3 V to 6 V, until you observe the pulses from the LED light.
- Measure the SiPM temperature using the PT 1000 and note the value in the provided spreadsheet.
- The histogram window shows the integral of the pulse between the two blue markers in the upper window. Several peaks should be visible, corresponding to pulses with 0, 1, 2, … photoelectrons. Adjust the LED pulse intensity until you see the maximum of the histogram at 1 or 2 photoelectrons. Perform a Gaussian fit of the peaks for 1 and 2 photoelectrons. Adjust the fit range using the cursors to cover the respective peaks. Note the obtained mean values in the spreadsheet.
- Calculate the average charge Q for a single photoelectron pulse based on the difference between the two peaks, taking into account the amplifier gain of 81 and the 50 Ohm measurement resistor of the oscilloscope. Calculate the SiPM gain G using equation 2. *[Optional: fit also the 4^{th} and 5^{th} peak of the histogram and use the average of the differences between the mean values to calculate the charge and SiPM gain.]*
- Repeat the measurement and analysis three more times for different bias voltages below and above the nominal one: -0.5 V, +0.5 V, +1.0 V. Plot gain versus operation voltage and obtain the breakdown voltage V_{BD} from a linear fit.
- Calculate the capacitance C_D (equation 2) and use it together with R_Q to determine the expected fall time of the signal (equation 1). Compare it to the fall time observed on the oscilloscope.
- Calculate the depth d of the avalanche volume, assuming that the capacitance of each APD is given by its geometry:
  $C_D=\varepsilon_{Si}*\varepsilon_0*\varepsilon_{geom}*A/d$,
  with $\varepsilon_{Si}=11.7$, $\varepsilon_0=8.854*10^{-12}$ F/m. The geometric acceptance ε_{geom} is about 70% (see Fig. 1) and the area A of a single APD is given by the total area of the APD array divided by the number of APDs.