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SiPM Characteristic Measurement Experiment

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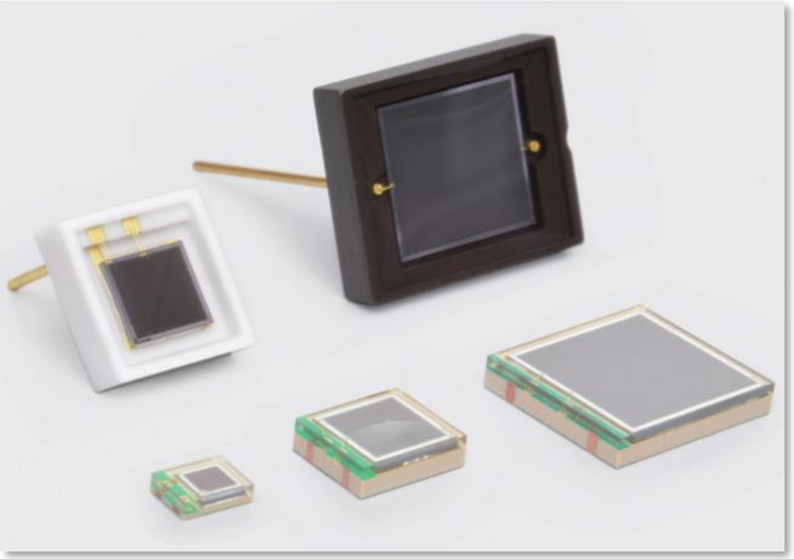
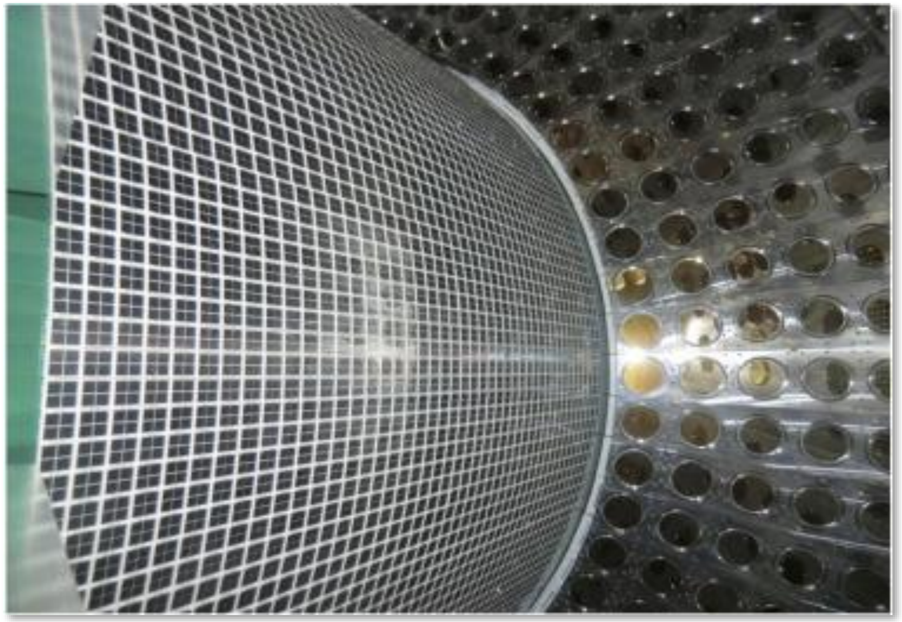
Introduction to SiPM

➢ Photodetector

➢ In particle physics experiments, it is often necessary to convert visible light into electrical signals. Therefore, high-precision photodetectors are of great importance. The silicon photomultiplier (SiPM) is a commonly used semiconductor photodetector with single-photon sensitivity.。



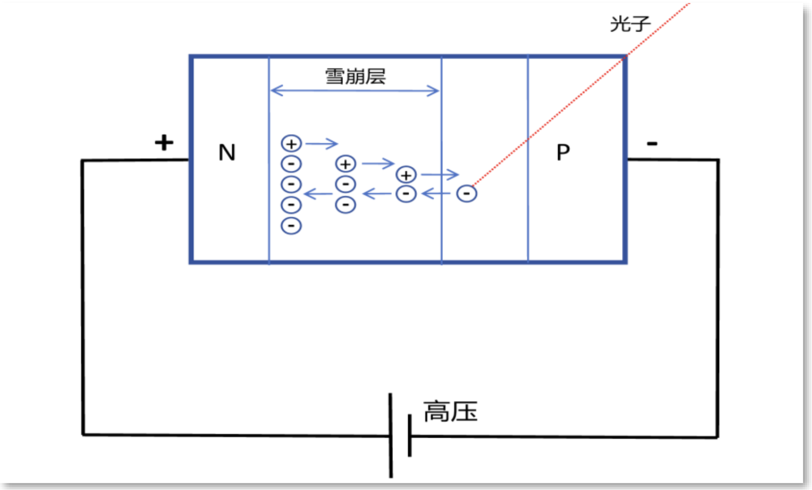
Photograph of a real SiPM



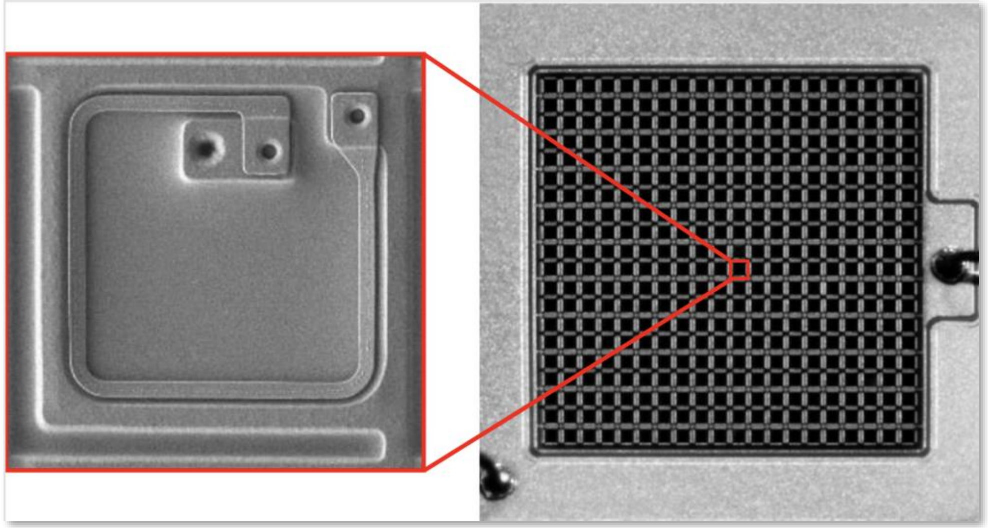
SiPM in particle physics detectors

Baldini A.M., et al., MEG II Collaboration, The design of the MEG II experiment, Eur. Phys. J. C, 78 (5) (2018).

Structure and Principle



Schematic of APD avalanche breakdown



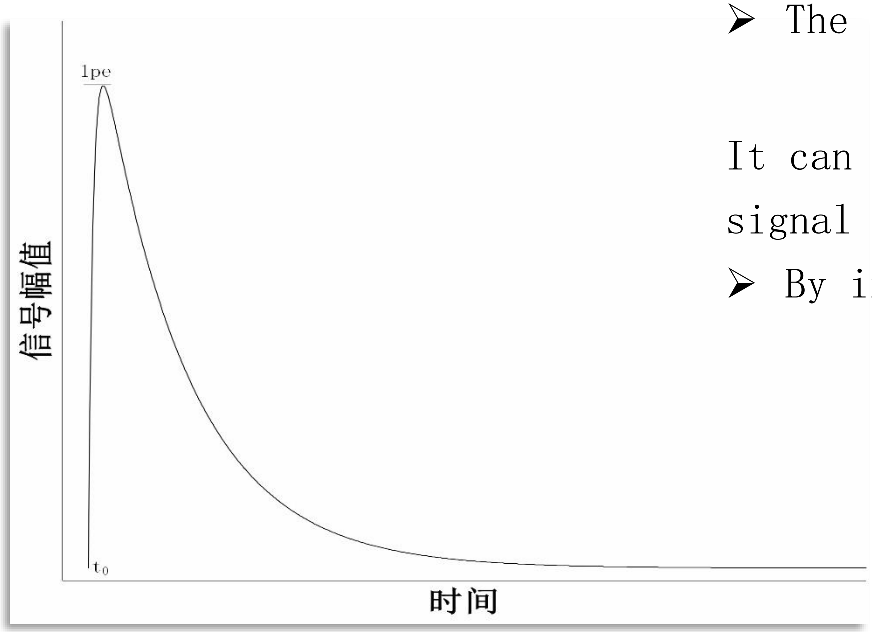
Actual SiPM structure; left figure shows a single GAPD cell
A.GHASSEMI, et al. Hamamatsu 2022[M]. 2022.

- The basic building block of an SiPM is an avalanche photodiode (APD) formed by a silicon PN junction. Through avalanche breakdown of the PN junction, the number of electrons is multiplied, so that a single-electron signal eventually becomes a macroscopically observable current signal, thus enabling single-photon detection.

- The APD used in SiPMs is a Geiger-mode APD (GAPD). Its characteristic is that once one electron is excited, it triggers the entire depletion region to break down, providing high-precision discrimination for single photons. However, it loses the ability to resolve photon energy and exact number.

- Therefore, many GAPD cells are combined to form an SiPM, where the number of photons is represented by the number of fired GAPD pixels.

Basic Characteristics



Schematic of SiPM signal

- The SiPM signal waveform can be described by the following formula:

$$U = A\left(1 - e^{-t/\tau_R}\right)e^{-t/\tau_F}\,.$$

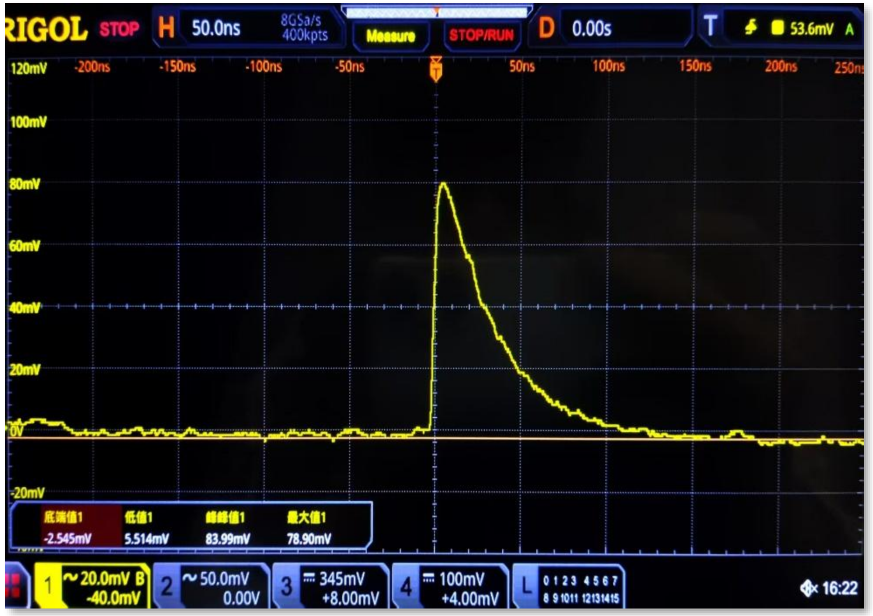
It can be simply considered that the SiPM signal is an exponential signal with a fast rising edge and a slower falling edge.

- By integrating the above formula, we obtain:

$$Q = \int_0^\infty \frac{U}{R}dt = \int_0^\infty \frac{A}{R}\left(1 - e^{-t/\tau_R}\right)e^{-t/\tau_F}\,dt = \frac{A}{R}\frac{\tau_F^2}{\tau_R + \tau_F} \approx \frac{A}{R}\tau_F\,.$$

- It can be considered that the SiPM signal amplitude is proportional to the charge.

- The SiPM charge output is discrete — so is the SiPM signal amplitude.



Measured SiPM signal waveform

Basic Characteristics

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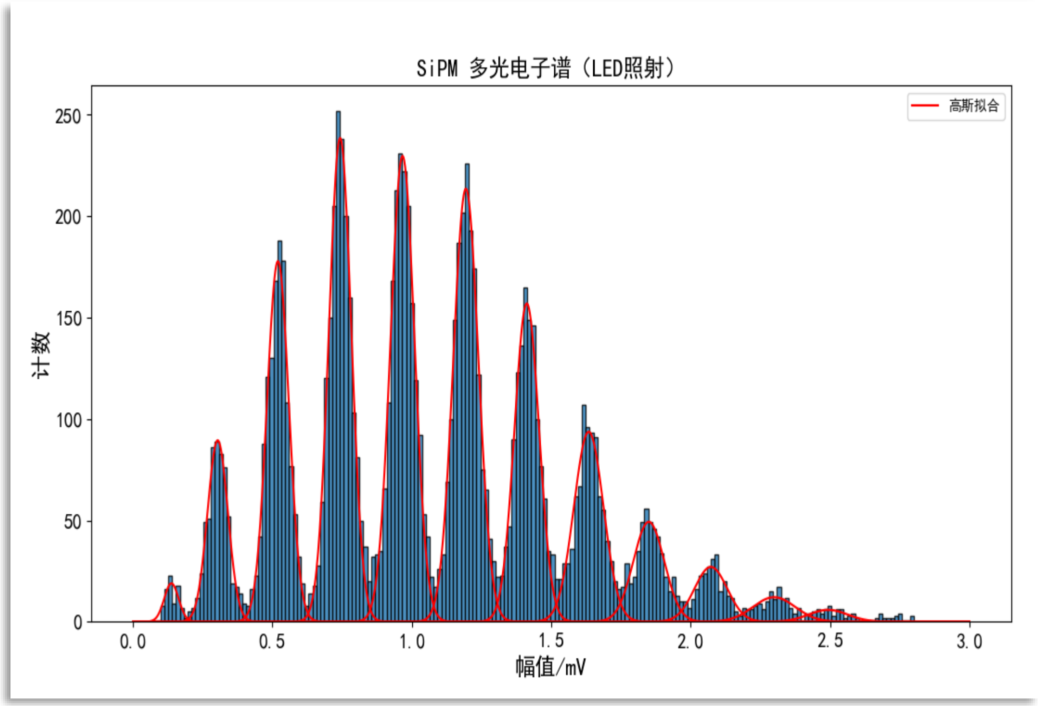
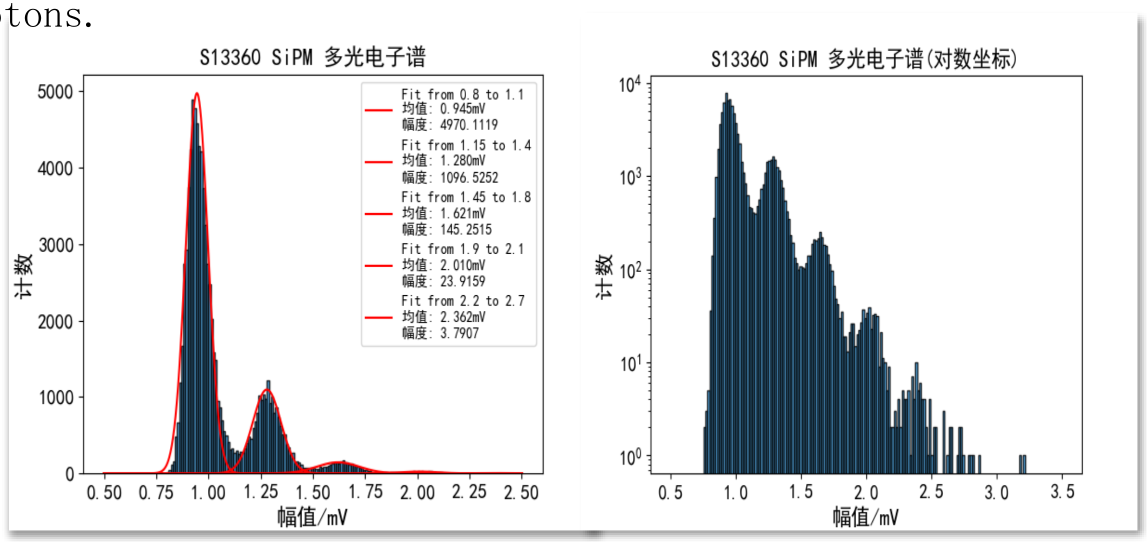
➢ Multi-photoelectron spectrum



Multi-photoelectron spectrum
under LED illumination

- The output amplitude/charge of an SiPM is discrete. When plotted as a histogram by frequency, many discrete peaks can be seen. The spacing between peaks is constant (corresponding to the output of a single pixel). Such a histogram is called the multi-photoelectron spectrum of the SiPM.
- Under illumination, the peaks of the multi-photoelectron spectrum follow a Poisson distribution, corresponding to the distribution of the number of received photons.。
- In a dark environment, the peak heights decrease exponentially, because the signals here originate from thermal excitation and crosstalk rather than real photons.



Multi-photoelectron spectrum in a dark environment

Basic Characteristics

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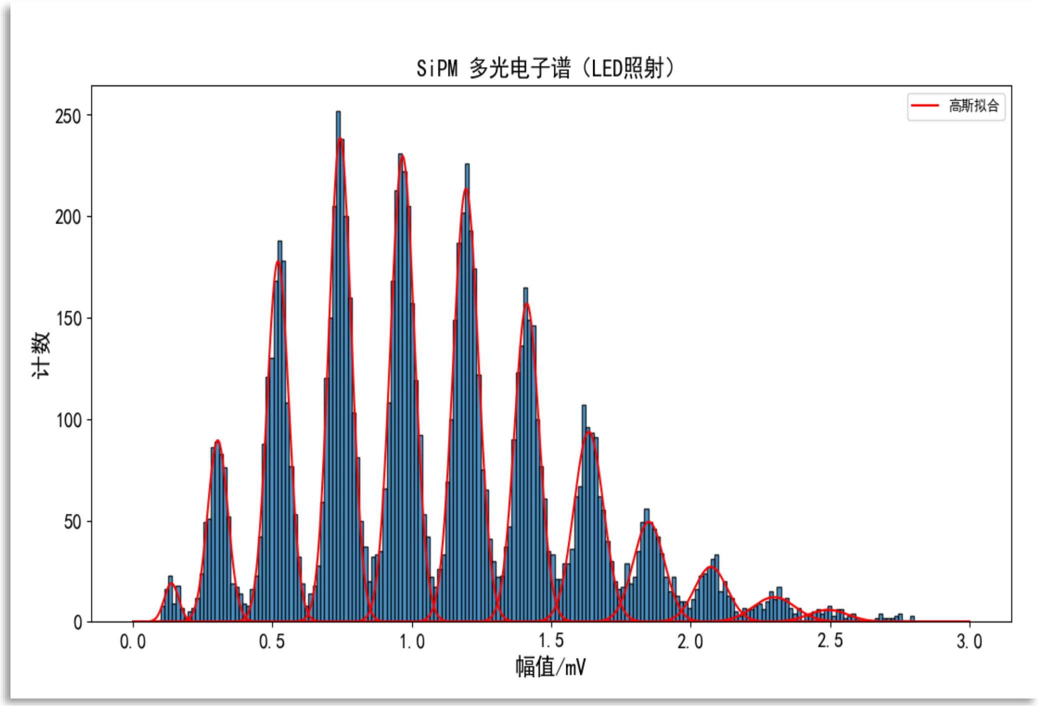
➢ Gain and Breakdown Voltage

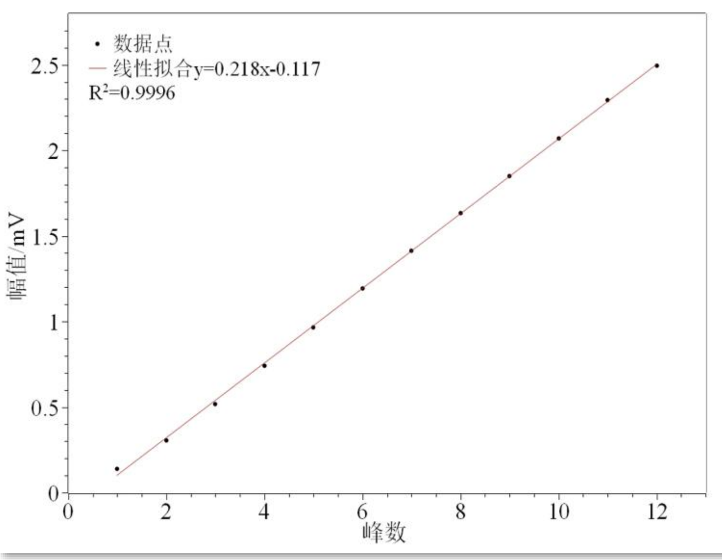


Multi-photoelectron spectrum under LED illumination

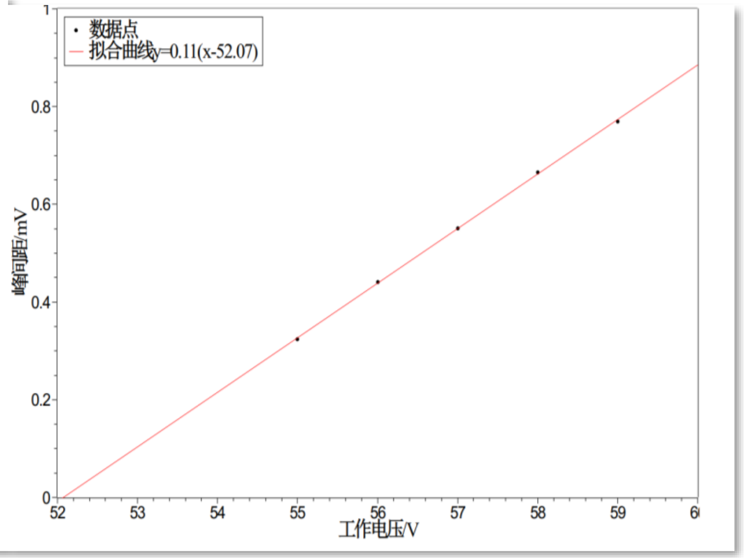
- The gain of a SiPM is defined as the ratio of the charge generated by a single microcell to the elementary charge:

$$G = \frac{Q}{e} = \frac{C \cdot (V_{bias} - V_{br})}{e}.$$

- Thus the output charge/amplitude is proportional to the overvoltage, i.e., the difference between the operating voltage and the breakdown voltage.
- The single-cell output can be obtained from the peak spacing of the multi-photoelectron spectrum. By fitting the gain-voltage relationship, the breakdown voltage of the SiPM can be determined.



Peak Number vs. Amplitude



Peak Spacing vs. Operating Voltage

Basic Characteristics

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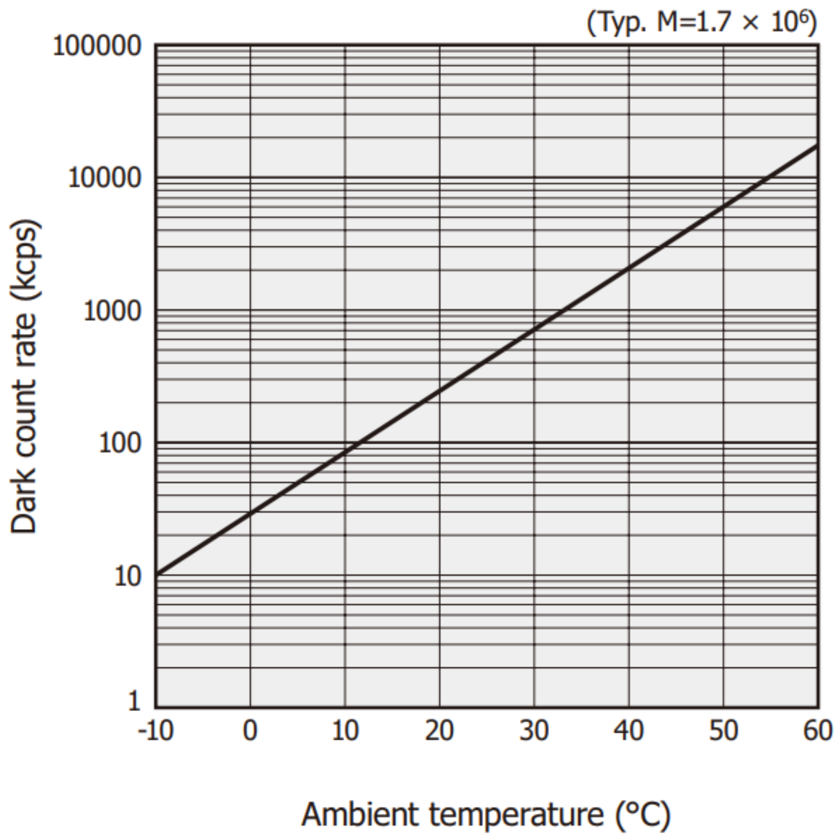
➢ Dark Count Rate

- Signals generated by a SiPM in complete darkness are called dark counts, which constitute one of the primary noise sources in photon detection. The Dark Count Rate (DCR) depends on several factors, including: temperature, overvoltage, discrimination threshold and so on.

- Since dark counts mainly originate from thermally generated carriers, their temperature dependence can be described by the Fermi‑Dirac distribution:

$$f_e(E,T) = \frac{1}{1+\exp\left(\frac{E-E_F}{kT}\right)} \approx \exp\left(-\frac{\Delta E}{kT}\right).$$

- The dark count rate decreases exponentially as the temperature decreases.

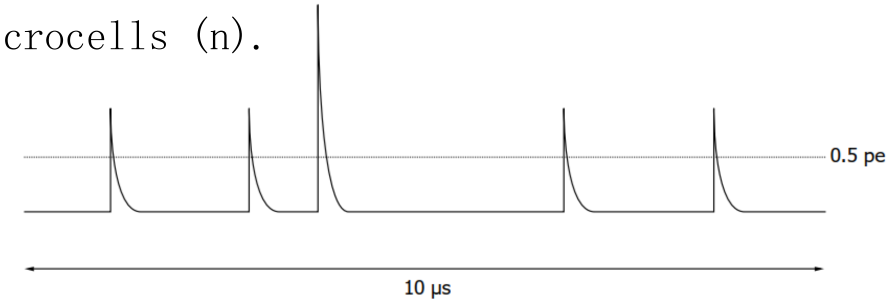


Dark Count Rate versus Temperature

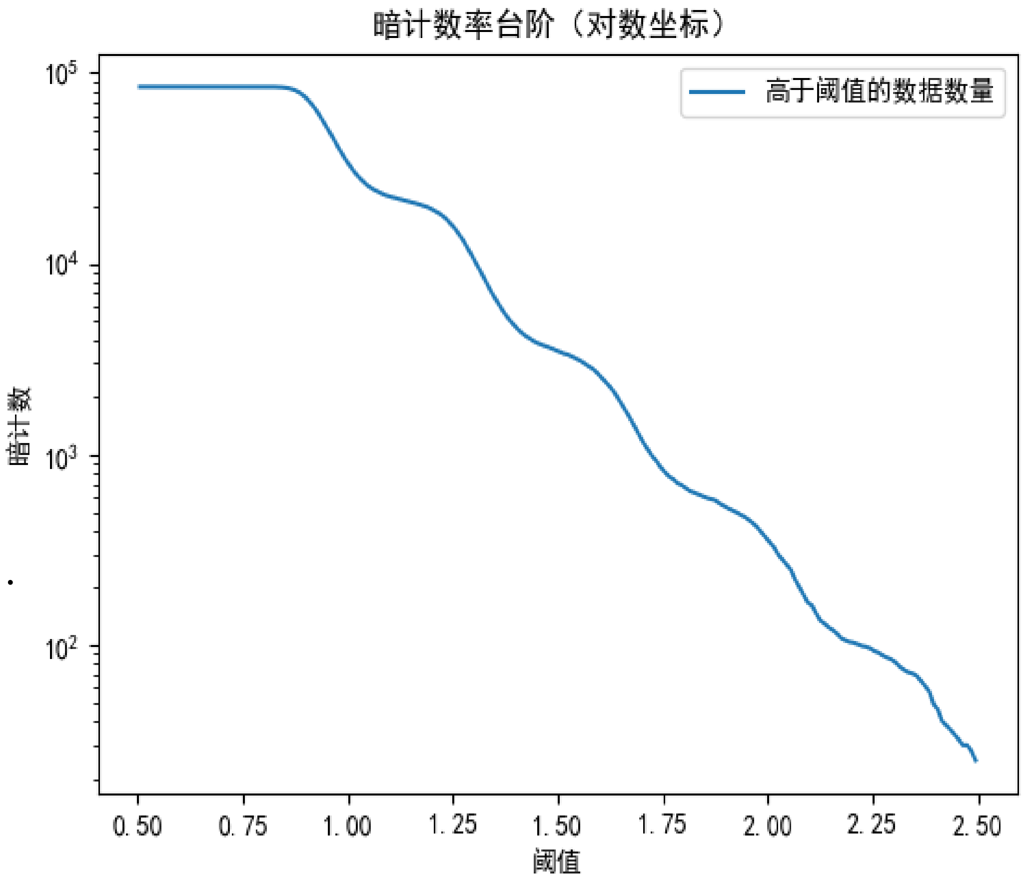
Basic Characteristics

➢ Dark Count Rate

- The dark count rate also decreases in a stepwise manner as the discrimination threshold (signal amplitude) increases.
- Assuming randomly distributed dark signals, if the probability of observing an event within a given time window is P, then the probability of observing n events follows P^n.
- In practice, signals exceeding the single-photoelectron amplitude are mainly caused by optical crosstalk. If the crosstalk probability is denoted by $F(P)$. Then the dark count rate of an n-photoelectron signal is proportional to $F(P)^{n-1}$.
- The dark count rate decreases exponentially with the number of fired microcells (n).

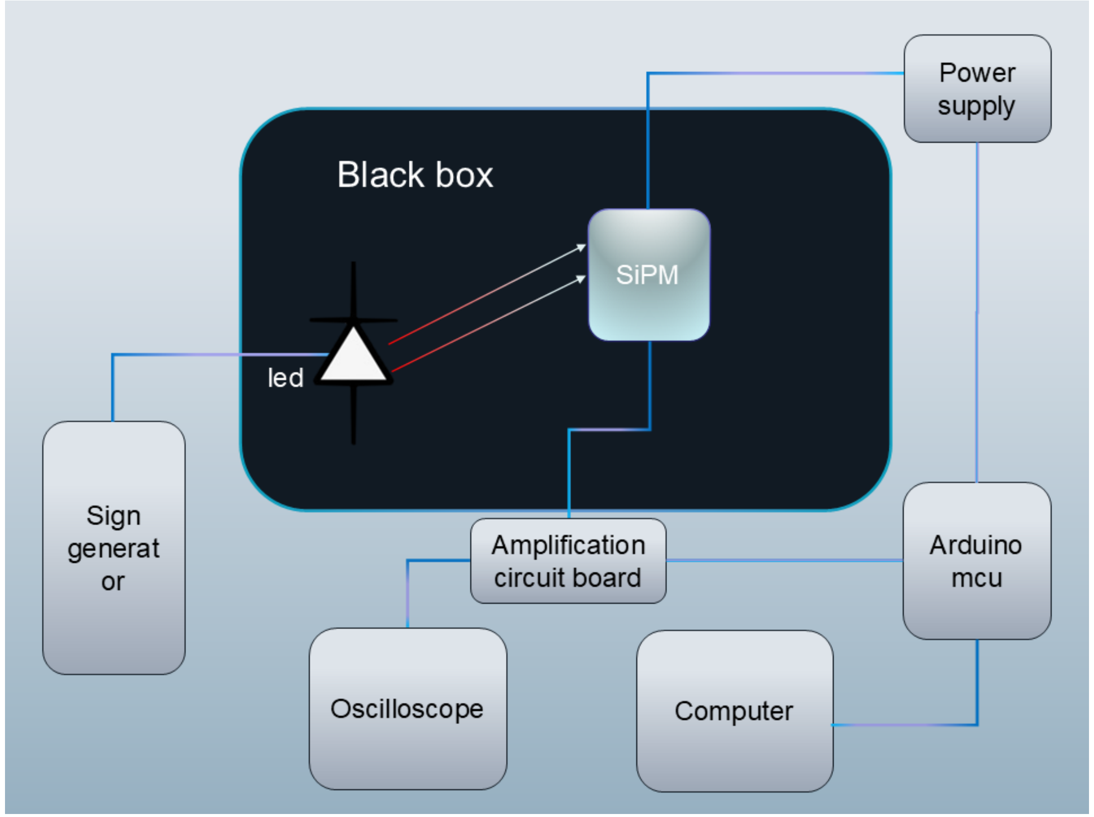


Randomly Distributed Dark Signals

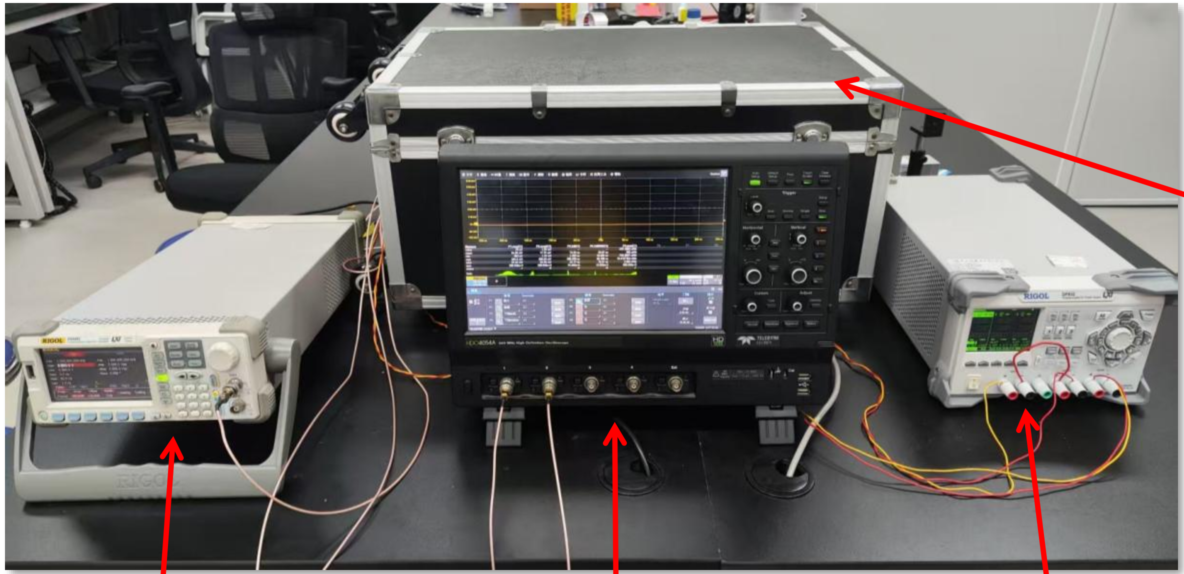


Dark Count Steps

Experimental setup



Schematic of Experimental setup



◆ Black box

◆ signal generator ◆ oscilloscope ◆ DC power supply

THANKS

谢谢大家