Operation Principle of Silicon Photomultipliers

Multi-Pixel Photon Counter (MPPC)

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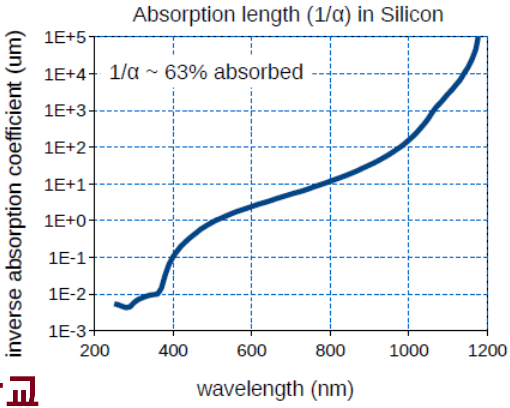
Principle of Photon Detection

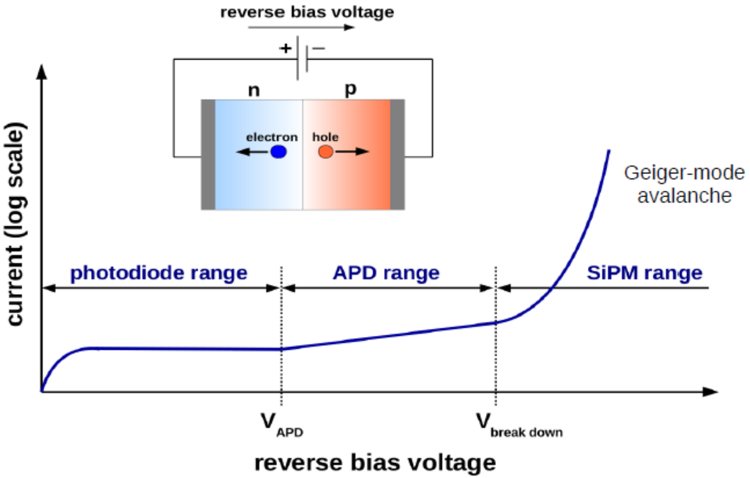
- Photoelectric effect produces electron-hole pairs. Band gap (T = 300 K) = 1.12 eV (1100 nm).
- The electron-hole pair can be lost via absorption and recombination.



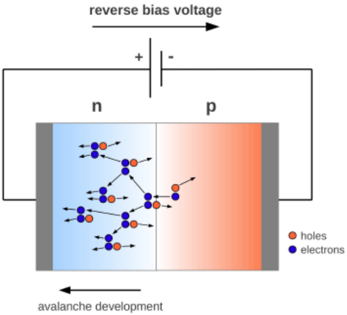
Green MA, Keevers MJ. Progress in Photovoltaics 1995, 3:189 - 192

Operation Range

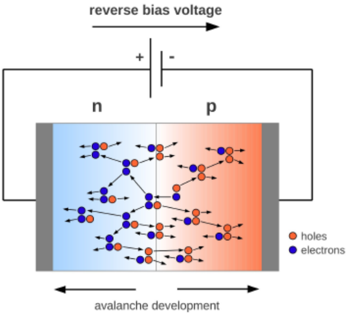
- The primary electron-hole pair is amplified.



Avalanche Modes



proportional (APD) mode



Geiger-APD (SiPM) mode

- Only electrons contribute to the avalanche in APD (Proportional) mode.
- Avalanche is self-quenched.

- Electrons and holes contribute to the avalanche in Geiger-APD (SiPM) mode.
- Avalanche is sustained, and external quenching is necessary with a resistor.

Photodiode in Geiger Mode

- A photodiode operated in Geiger mode is referred to as a SPAD (Single Photon Avalanche Diode).
- The application of a reverse bias beyond its nominal breakdown voltage creates the necessary high-field gradients across the junction.
- Once a current flows, it should then be stopped or ‘quenched’.
- Passive quenching is achieved through the use of a series resistor R_Q which limits the current drawn by the diode during breakdown.
- This lowers the reverse voltage seen by the diode to a value below its breakdown voltage, thus halting the avalanche. The diode then recharges back to the bias voltage, and is available to detect subsequent photons.

Cycle of breakdown, avalanche, quench and recharge of the bias to a value above the breakdown voltage

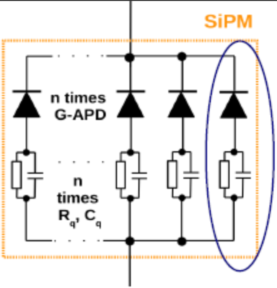
Single Photon Avalanche Diode in Geiger Mode

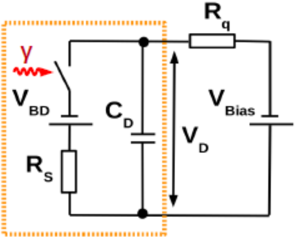
- A single SPAD sensor operated in Geiger-mode functions as a photon-triggered switch, in either an 'on' or 'off' state.
- Regardless of the number of photons absorbed within a diode at the same time, it will produce a signal no different to that of a single photon. Proportional information on the magnitude of an instantaneous photon flux is not available.

Single Photon Avalanche Diode in Geiger Mode

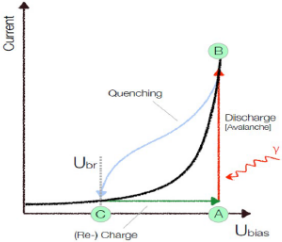
- To overcome this lack of proportionality, the MPPC integrates a dense array of small, independent diodes (microcells), each with its own quenching resistor.
- When a microcell fires in response to an absorbed photon, a Geiger avalanche causes a photocurrent to flow through the microcell.
- This results in a voltage drop across the quench resistor, which in turn reduces the bias across the diode to a value below the breakdown, thus quenching the photocurrent and preventing further Geiger-mode avalanches.
- Once the photocurrent has been quenched, the voltage across the diode recharges to the nominal bias value (the recovery time).

Quenching





C_D: diode capacitance
R_S: silicon substrate serial resistor
V_{BD}: breakdown voltage

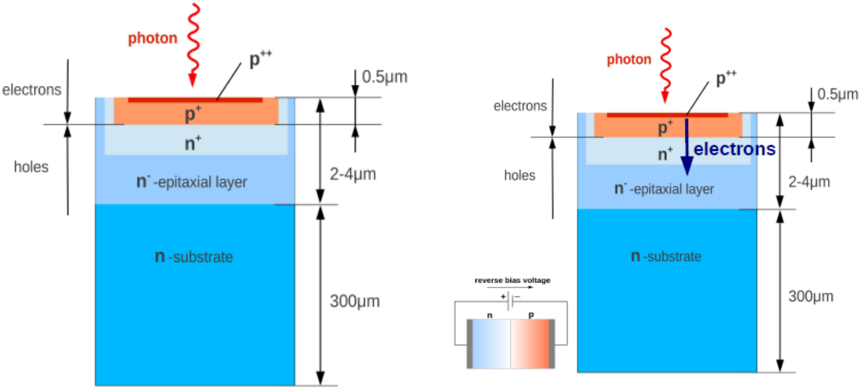


$A \rightarrow B$ avalanche triggered, discharge of C_D to V_{BD}.

$B \rightarrow C$ voltage drop on R_q quenches the avalanche.

$C \rightarrow A$ C_D recharges via the quench resistor (fast recharge induces high afterpulsing).

MPPC: p on n



- More sensitive in the blue and near UV light because of electrons produced near the p^{++} layer triggering the avalanche.

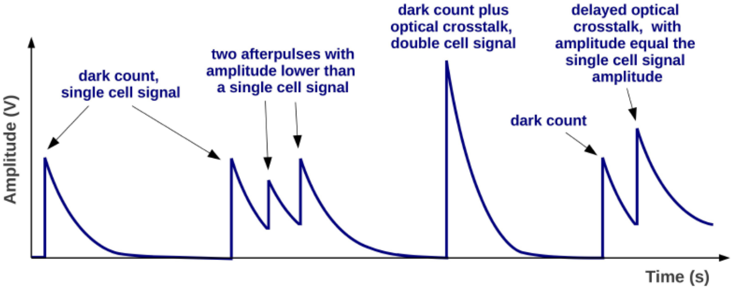
Photon Detection Efficiency

- The PDE is the statistical probability that an incident photon interacts with a microcell to produce an avalanche:

$$PDE(\lambda, V) = \eta(\lambda) \cdot \varepsilon(V) \cdot F,$$

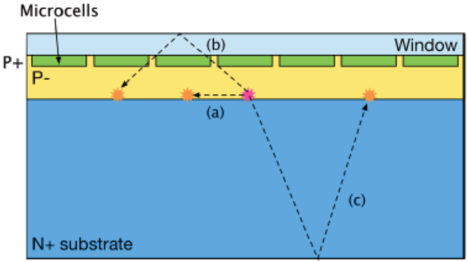
where $\eta(\lambda)$ is the quantum efficiency of silicon, $\varepsilon(V)$ is the avalanche probability and F is the fill factor.

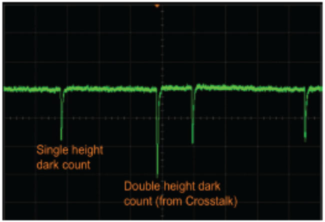
MPPC Signal



- Dark currents
- Afterpulses : carriers trapped during the avalanche
- Cross-talk

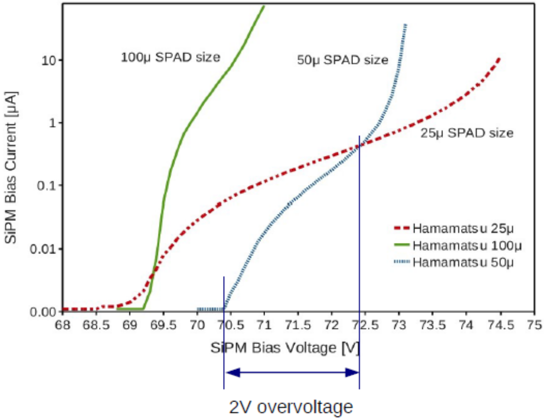
Optical Crosstalk





- During avalanche, accelerated carriers in the high-field region will emit photons that can initiate a secondary avalanche in a neighboring microcell.
- These secondary photons tend to be in the near infrared region and can travel long distances.
- A single incident photon may generate signals equivalent to 2 or 3 photons or even higher.

I-V Curve and Breakdown Voltage



- In Geiger-mode avalanche mode , parameters such as photon detection efficiency (PDE), single photon time resolution, dark count rate, crosstalk or afterpulse are dependent on overvoltage not bias voltage.
- Breakdown voltage strongly temperature dependent (50 mV/K)

Signal Model [1]

- The MPPC output current during the rising and quenching transient operations can be written as a function of time:

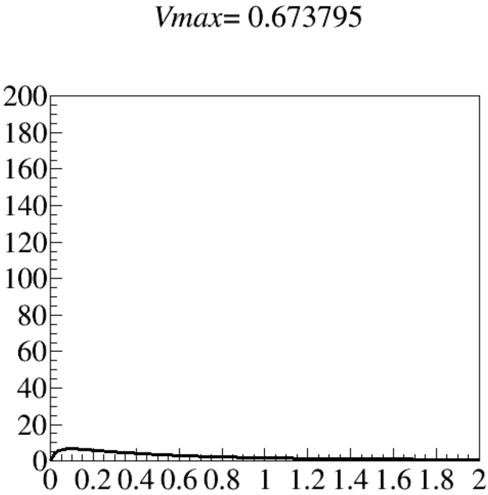
$$i_{R_L}(t) = I_f\left(1 - \frac{\tau_q - \tau_i}{\tau_d - \tau_i} e^{-t/\tau_i} + \frac{\tau_q - \tau_d}{\tau_d - \tau_i} e^{-t/\tau_d}\right),$$

where the circuit time constants τ_i and τ_d account for the rising and quenching processes. $\tau_q = R_q C_q$. The final current value is given by

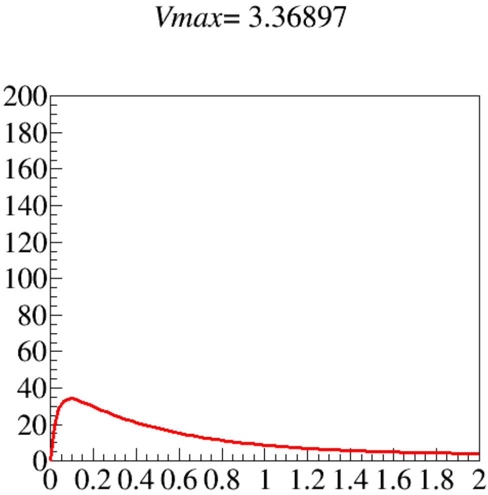
$$I_f = N_f \frac{V_{over}}{R_q + R_d + N_f R_L}$$

[1] D. Marano *et al.*, IEEE Tran. Nucl. Sci. 61, No 1, 23 (2014)

Simulated Pulses



Simulated Pulses



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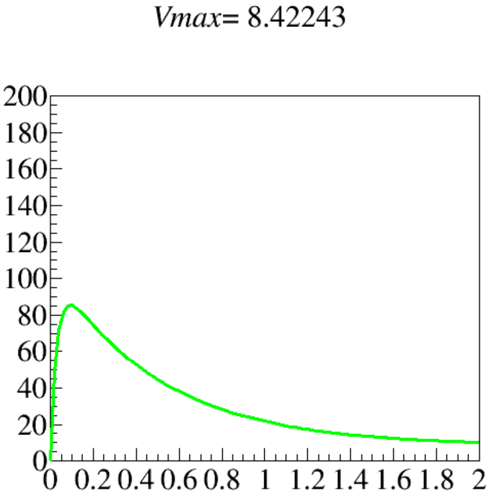
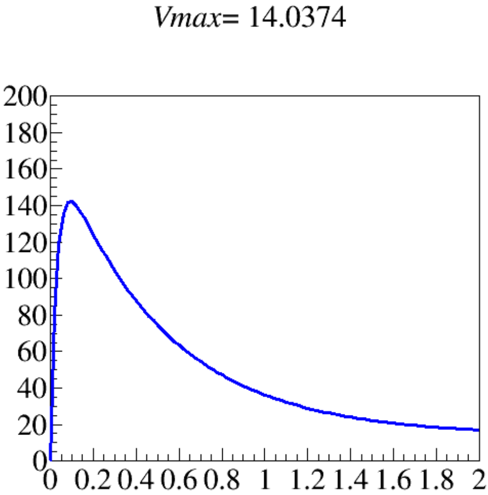
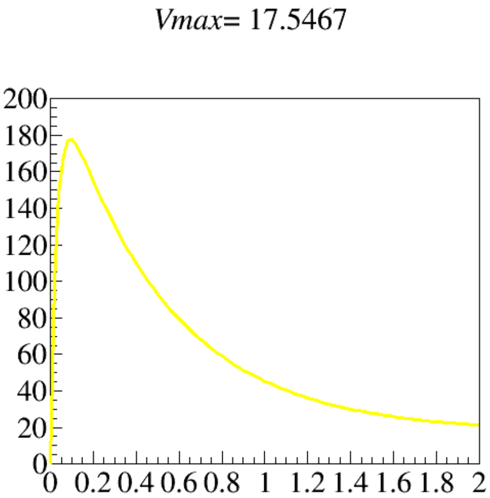
Simulated Pulses



Simulated Pulses



Simulated Pulses



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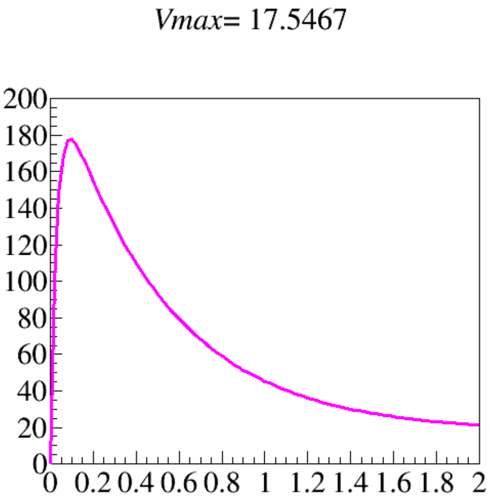
Simulated Pulses



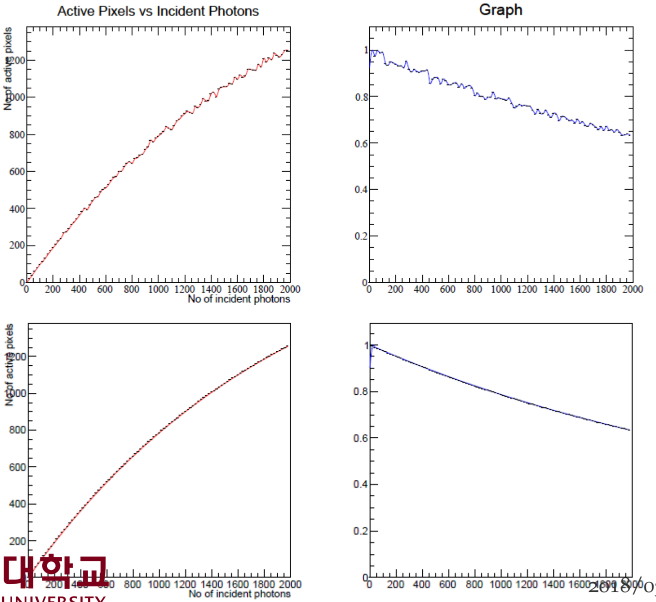
Signal Simulation

- Number of photoelectrons obeys Possion Statistics.
- Crosstalks happends randomly. The spatial distribution can be assumed as a random walk in 4 or 8 directions.
- Random pulse arrival times.
- Electronic noise terms.
- Dark current
- Afterpulses

Occupation Probability

```
Int_t npho = 0;
for (Int_t ipho=1; ipho<Ncell; ipho++) {
   if(ipho\%10==0) { npho++;
     prob0[0]=0.; prb0[1]=1./Ncell;
     Float_t sumocc = 0;
     for (Int_t ir=1; ir<=ipho; ir++) {
       occ[ir-1] = 1 - prb0[ir-1];
       Float_t prb00 = 0;
       for (Int_t ip=1; ip<=ir; ip++) {
         prb00 += 1./Ncell * occ[ip-1];
       }
       if(ir>1) prb0[ir] = prb00;
       occ[ir] = 1 - prb0[ir];
       sumocc += occ[ir];
     }
     phot[npho] = (double)ipho;
     socc[npho] = sumocc;
     ratio[npho] = socc[npho]/phot[npho];
```

Occupation Probability

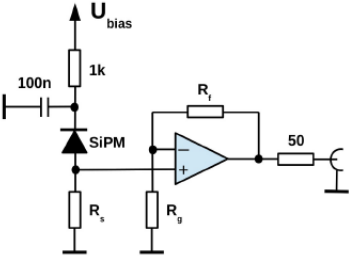


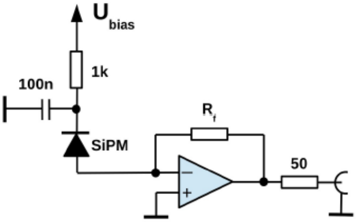
Summary

- A signal model for an MPPC with thousands of microcells will be tested with a measurement of MPPC signals with an LED source.

Backup

Signal Amplifiers

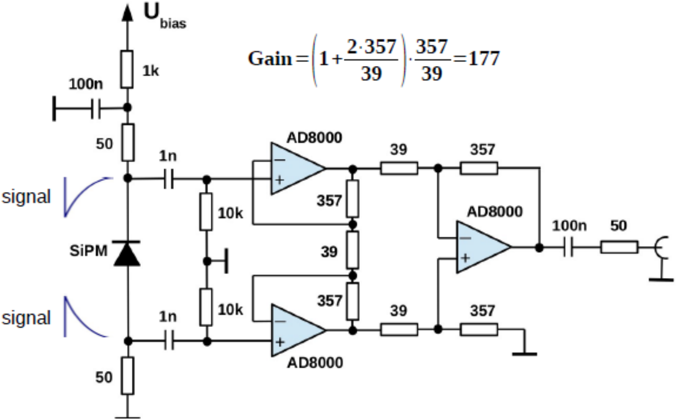




- Very stable.
- Low R_s needed for fast SiPM signal $\rightarrow$ low signal-to-noise ratio.
- Gain = R_f/R_g typically 10 to 100.

- Tendency to oscillations, less stable.
- Very low input impedance $\rightarrow$ preferred readout for SiPMs.
- Gain is defined by R_f.

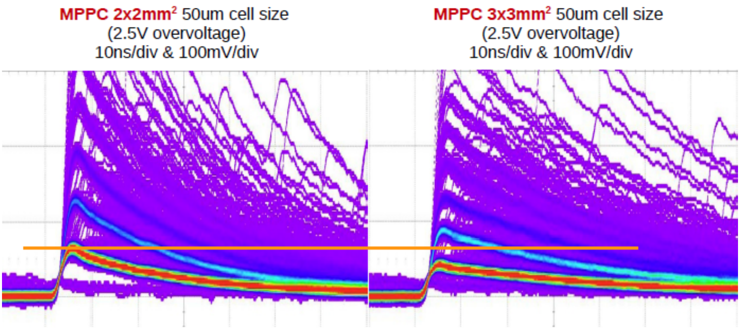
Voltage Amplifier



$$Gain = \left(1 + \frac{2 \cdot 357}{39}\right) \cdot \frac{357}{39} = 177$$

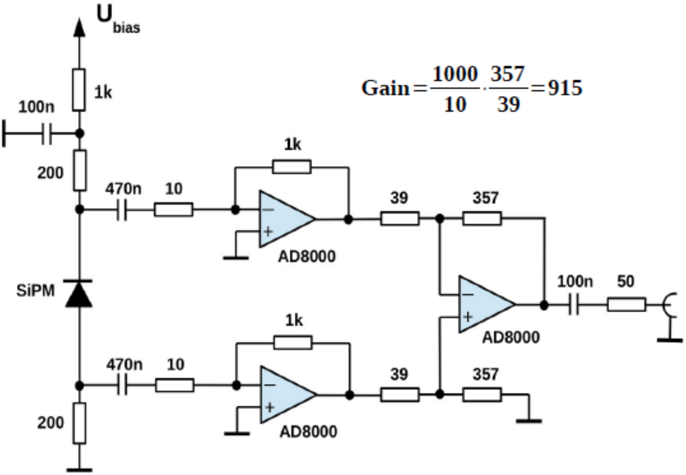
- Differential readout suppresses low to medium high frequency pick-up.

Voltage Amplifier



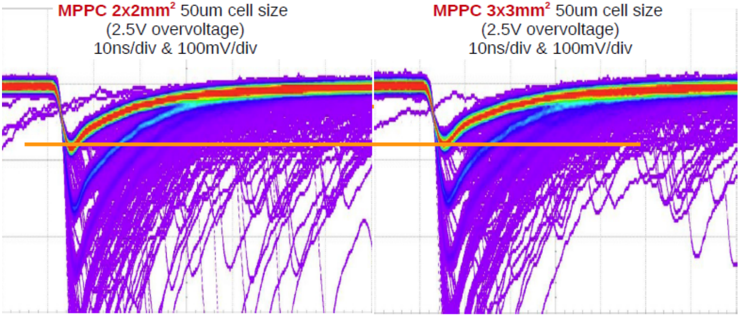
- Signal becomes lower if device size (capacitance) gets larger due to capacitive divider (quenching and SiPM terminal capacitance).

Transimpedance Amplifier



- Differential readout suppresses low to medium high frequency pick-up.

Transimpedance Amplifier



- Signal stays the same for different device sizes, if input impedance of amplifier is lower than device impedance.

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