

Introduction to silicon photomultipliers (SiPMs)

Basic structure and operation

The silicon photomultiplier (SiPM) is a radiation detector with extremely high sensitivity, high efficiency, and very low time jitter. It is based on reversed biased p/n diodes and can directly detect light from near ultra violet to near infrared. SiPMs are employed in all those applications where low light/radiation levels must be measured and quantified with high precision.

Light is made of photons (quantum of light). SiPMs are designed to have high gain and high detection efficiency so that even a single photon impinging on a SiPM pixel can be detected producing an output current pulse with a very low time jitter (<100 ps). The structure of a SiPM allow “parallel” photon detection, meaning that more photons can be detected at the same time enabling photon counting.

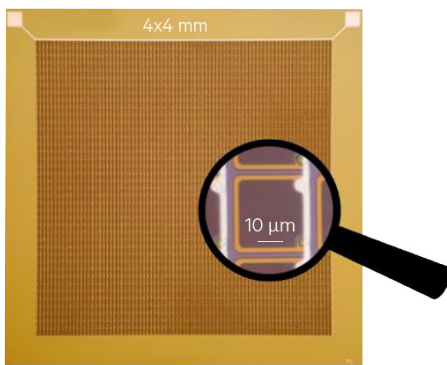
A SiPM consists of a matrix of small-sized sensitive elements called micro-cells (or pixels) all connected in parallel (Figure 1 and 2). Each micro-cell is a Geiger-Mode avalanche photo-diode (GM-APD) working beyond the breakdown voltage (V_{bd}) and it integrates a resistor for passive quenching.

The equivalent circuit of a GM-APD is shown in Figure 3. C_d is the diode capacitance in reverse bias, R_s is the silicon substrate series resistance, and R_q is the quenching resistor ($R_q \gg R_s$). There are three fundamental operation modes in a GM-APD: quiescent mode, discharge phase, recovery phase.

In quiescent mode, the diode is reversed biased to $V_{bias} = V_{bd} + V_{ov}$ (V_{ov} is the over-voltage, i.e. the excess bias beyond V_{bd}). The

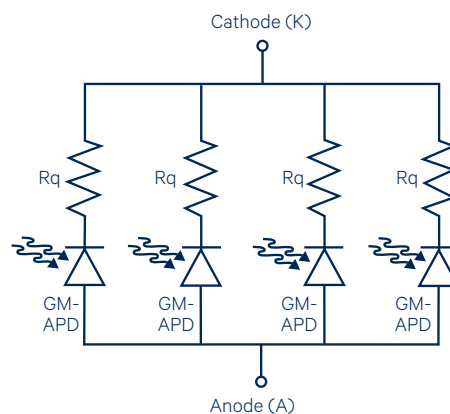
switch in the equivalent circuit of Figure 3 is open and unless a photon is absorbed (or a dark event occurs), the diode remains in this condition with no current flowing (neglecting leakage currents). When a photon is absorbed (or a dark event occurs), the equivalent model prescribes that the switch closes and C_d discharges from V_{bias} to V_{bd} through R_s : during this phase, avalanche multiplication is ongoing inside the GM-APD. Once triggered, the avalanche process is self-sustaining meaning that, without quenching, a steady current flows indefinitely in the device. With R_q , the avalanche process is quenched and the switch in the equivalent circuit of Figure 3 opens again. The GM-APD enters now the recovery phase: C_d recharges back to V_{bias} through R_q and the GM-APD returns in the quiescent mode, ready for the detection of a new photon.

Figure 1



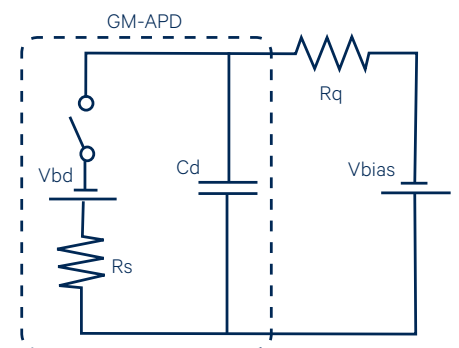
Picture of a 4x4 mm² SiPM die. The SiPM consists of a matrix of micro-cells all connected in parallel. Each micro-cell is a GM-APD and it represents the basic sensitive element of the SiPM.

Figure 2



The parallel arrangement of GM-APDs with series quenching resistors (R_q) in a SiPM.

Figure 3



The equivalent circuit of a GM-APD with series quenching resistor and external bias. The switch models the turn-on (photon absorption or dark event) and turn-off (quenching) probabilities.

Introduction to silicon photomultipliers (SiPMs)

The Cd discharge and recharge appears at the SiPM terminals as a current pulse, see Figure 4. The rising edge corresponds to the discharge phase (time constant $C_d \times R_s$), while the slower trailing edge is the recovery phase with time constant $C_d \times R_q$. To mention that the quenching time is negligible. The amplitude of the SiPM pulse increases with the overvoltage while both the rising time and the recovery time are mainly determined by C_d , R_s , and R_q .

During recovery, the GM-APD cannot detect other photons⁽¹⁾. For this reason, a GM-APD cannot count the number of incoming photons unless the photon rate is lower than the inverse of the recharge time. SiPMs overcome this limitation thanks to the parallel arrangement of several micro-cells. When N photons are detected (which means that N photons arrive on N different micro-cells producing N single-cell signals) the SiPM output pulse is N -times larger than the single-cell response. In that, the N independent

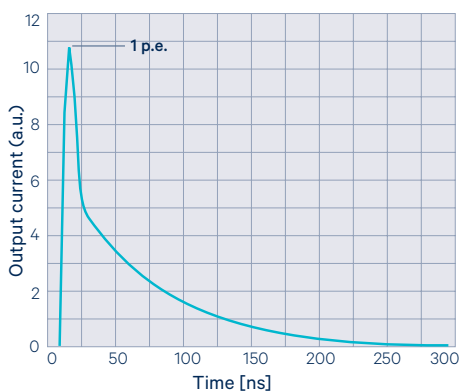
current pulses just add up at the SiPM terminals. Note that both the amplitude and the area of each SiPM pulse, which is the total charge delivered by the detector, are proportional to the number of detected photons (neglecting primary and correlated noise for the time being). If the number of incoming photons is larger than the number of micro-cells in the SiPM, saturation occurs and neither the amplitude nor the area of the output pulse can give information on the number of incoming photons anymore.

In the case of not concurrent cells firing, pile-up of pulses may occur at the SiPM terminals: as an example, Figure 6 shows three micro-cells firing in rapid sequence. As before, the area of the SiPM signal is proportional to the number of the detected photons, but it is less straightforward to retrieve information from the amplitude of the SiPM signal. The same applies when bunches of simultaneous photons reach the SiPM surface with a certain

time distribution: several pulses with different amplitudes may overlap in time.

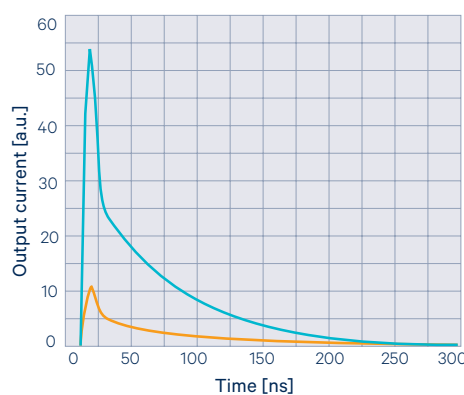
SiPMs can be employed to determine the characteristics of the incoming light. For instance, when SiPMs are coupled to scintillating crystals, the SiPM output signal mimics, in time, the characteristic light emission profile of the crystal itself (under the assumption that the decay time of the crystal is much longer than the recovery time of the SiPM and that the SiPM works in non-saturation). In an analog way, SiPMs are employed to evaluate also the characteristic fluorescence decay time of substances or molecules. By computing the integral of the SiPM signal one can determine the amount of charge produced by the SiPM, hence the amount of light emitted by the crystal and eventually the total energy deposited in the crystal, obtaining in this way information on the type (energy) of the radiation being stopped by the crystal (i.e. spectroscopy).

Figure 4



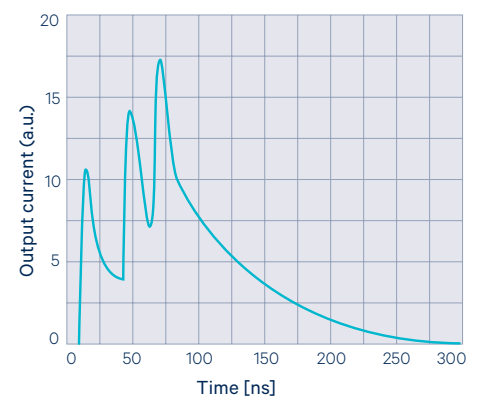
Current pulse produced by a micro-cell in response to photon absorption (single-cell signal). The pulse has a very fast rising edge and a slower trailing edge (micro-cell recovery). Its amplitude is defined to be 1 p.e. (photo-electron).

Figure 5



Typical SiPM pulse (blue curve) corresponding to simultaneous firing of several cells. The single-cell signal is also reported (orange curve). The SiPM amplitude and pulse area are proportional to the number of detected photons at the same time.

Figure 6



Pile-up in a SiPM. Three different micro-cells fire at different times. The SiPM output pulse is the sum of the three single-cell signals. The SiPM signal area (i.e. the total charge delivered by the SiPM) is proportional to the number detected photons.

(1) During recovery the voltage across the GM-APD is increasing from V_{bd} to $(V_{bd} + V_{ov})$, according to the exponential recharge of C_d trough R_q . Consequently, the detection efficiency goes from zero to the value at V_{ov} with the same time constant. The micro-cells are thus not completely blind during recovery; they feature increasing detection efficiency.

Introduction to silicon photomultipliers (SiPMs)

Breakdown voltage

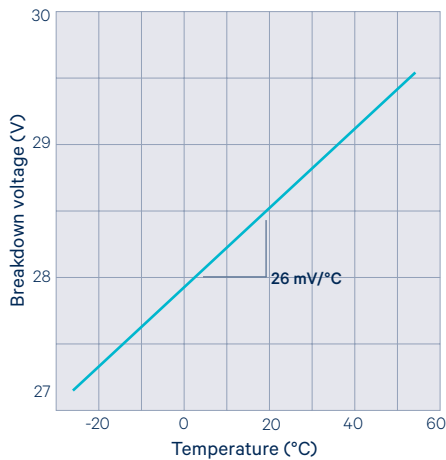
The breakdown voltage (V_{bd}) is the minimum (reverse) bias voltage that leads to self-sustaining avalanche multiplication in GM-APDs. In other words, it is the minimum bias for which output pulses as those shown in Figures 4-6 can be obtained. However, for $V_{bias} = V_{bd}$ both the detection efficiency and the gain of SiPMs are (by definition) still null. Only for $V_{bias} > V_{bd}$ output current pulses are actually observed. The excess bias beyond the breakdown voltage is called overvoltage (V_{ov}). By definition:

$$V_{ov} = V_{bias} - V_{bd}$$

In principle, the higher the overvoltage, the higher the SiPM performances. In reality, since the detection efficiency tends to saturate with V_{ov} while the noise keeps on increasing (even more than linearly) with V_{ov} , there exist an upper limit to the optimum SiPM bias voltage. The breakdown voltage is defined by the p/n junction characteristics of the particular SiPM technology. SiPMs from First Sensor feature V_{bd} in the range of 25-29 V at room temperature, and are designed to work in the overvoltage range of 2 to 5 V (refer to the SiPM datasheets).

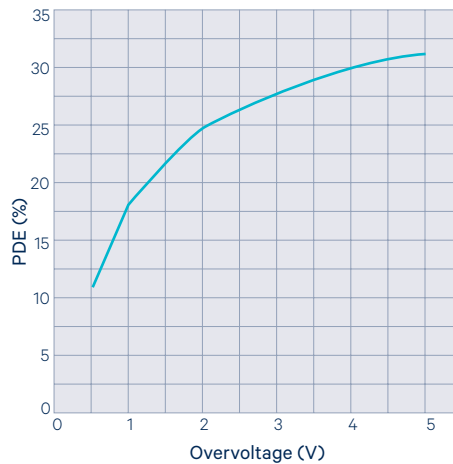
Also the temperature dependence of the breakdown voltage is determined by the structural characteristics of the GM-APDs. An example of the V_{bd} temperature variation in the SiPMs from First Sensor is reported in Figure 7. For more details, refer to [1].

Figure 7



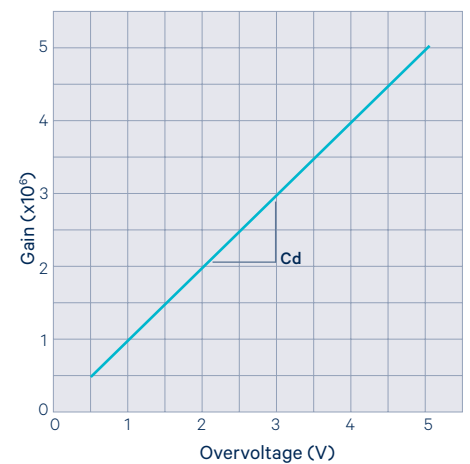
Breakdown voltage temperature dependence. The temperature coefficient (slope) is 26 mV/°C.

Figure 8



Photon detection efficiency (PDE) as a function of the overvoltage. The PDE tends to saturate at high overvoltage because of the saturation of the Pt. 560 nm incident light.

Figure 9



SiPM gain as a function of the overvoltage. The slope is the diode capacitance C_d .

Introduction to silicon photomultipliers (SiPMs)

Photon Detection Efficiency (PDE)

The photon detection efficiency (PDE) is the probability that a photon arriving on the SiPM surface is detected, producing an output pulse. It can be defined as the ratio between the number of detected photons over the number of incoming photons.

In terms of device characteristics, the PDE is defined as the product of three factors: quantum efficiency (Qe), triggering probability (Pt), and geometry efficiency (FF):

$$\text{PDE (Vov)} = \text{Qe} \times \text{Pt (Vov)} \times \text{FF}$$

Quantum efficiency (Qe) expresses the probability that a photon impinging on the SiPM is actually transmitted to the silicon, absorbed in the silicon and finally converted in an electron/hole pair. Qe is a function of the wavelength and angular incidence of incoming photons. The triggering probability (Pt) is the probability

that the generated electron/hole pair successfully initiates a self-sustaining avalanche process and thus an output current pulse. Pt is a strong function of the overvoltage, and it increases with Vov according to the electron and hole ionization rates dependence on the induced electric field [2]. Also Pt is wavelength-dependent since the avalanche initiation probability depends on the position inside the GM-APD where the electron/hole pair has been generated and this, in turn, depends on the wavelength of the incoming photon.

The geometry efficiency (or fill-factor, FF) accounts for the fact that each micro-cell in the SiPM has necessarily some dead area on its periphery to accommodate isolating structures and metal lines for signal routing. Figure 8 shows a typical PDE curve as a function of the overvoltage. The functional dependence of PDE on overvoltage is

contained in the Pt term since both Qe and FF are constant factors for a given wavelength. The main limiting factor in the PDE is the fill-factor: for sufficiently high overvoltage, in fact, both Qe and Pt are closed to 1 and PDE eventually saturates to FF.

By definition, we have $0 < \text{Qe}, \text{Pt}, \text{FF} < 1$. To maximize PDE, each of its three factors shall be optimized. Qe values as high as 0.98 are achieved by means of proper anti-reflecting coating layers deposited over the SiPM active area. Pt is maximized recurring to junction and electric field engineering [3]. Notably, the RGB and NUV SiPMs from First Sensor have different internal junction structure to maximize Pt for, respectively, visible light and near-ultra violet light [3],[4]. To enhance cells fill-factor one must recur to advance lithography techniques with sub-micron feature size and clever device layout [5].

Gain

The gain (G) is defined as the number of carriers contained in the single-cell current pulse since this is the number of carriers generated during the avalanche in response to an absorbed photon. From Figure 3 and relative discussion, the gain is given by the discharge of Cd from Vbias = (Vbd + Vov) to Vbd and therefore is given by the charge stored on a capacitor

of capacitance Cd with a potential difference of Vov, where q is the elementary charge:

$$\text{G (Vov)} = (\text{Cd} \times \text{Vov}) / q$$

Assuming Cd constant for Vbias > Vbd, gain increases linearly with the overvoltage, see Figure 9. Moreover, G is practically insensitive to temperature variations since Cd does not

vary appreciably with temperature (within a reasonable range of temperatures). At a given bias, any gain shift with temperature has to be ascribed to the breakdown voltage shift with temperature. At an overvoltage greater than 3 V, the SiPMs from First Sensor show gain variations of less than 1%/°C thanks to the low temperature coefficient of Vbd (see Figure 7).

Primary noise (Dark Count Rate)

Noise in SiPMs is represented by spurious output current pulses produced in absence of light. In silicon, there is a finite probability for carriers (electron and hole) to be generated by thermal agitation. During the quiescent mode, if an electron or hole originates inside the active region of a GM-APD an avalanche is initiated (with probability Pt) and an output pulse is observed. This is called a dark event. The number of dark events per unit time is the dark count rate (DCR). In silicon photomultipliers, the thermal generation of carriers doubles approximately every 10 °C, and so does the DCR. Moreover, the

DCR scales according to the SiPM area and it is an increasing function of the overvoltage.

In a single GM-APD a dark event is indistinguishable from a photo-generated one. In both cases, the output pulse has 1 p.e. amplitude, see Figure 4. In a SiPM, dark events still have 1 p.e. amplitude (neglecting direct optical crosstalk events, disused below) while the useful signal may consist of more photons impinging on the detector at the same time producing signals with amplitude greater than 1 p.e. (see also Figure 5). In this case, a

threshold can be set to, e.g., 1.5 p.e. to discard the dark events.

The DCR of a SiPM should be specified for a given SiPM size, micro-cell size, overvoltage and temperature. Since the primary noise scales with the silicon area, for a given SiPM technology, the DCR can be given as Hz (or cps) per unit area, with overvoltage and temperature always specified. In some cases, it could be useful to have the DCR specified for a certain PDE rather than a certain overvoltage.

Introduction to silicon photomultipliers (SiPMs)

Correlated noise: afterpulsing, optical crosstalk, ECF

Besides the primary noise, in SiPMs there are other two sources of noise, i.e., afterpulsing (AP) and optical crosstalk (OC). Both AP and OC events originate from an existing current pulse (which can be either a photon-event or a dark-event) and for this reasons they are referred as to correlated noise. The probability of having an AP or OC event strongly depends on the current density in the original avalanche and on the triggering probability Pt. Large micro-cells have large gain, hence a high number of carriers flowing during the avalanche and thus high AP and OC probability. To contain the correlated noise it is essential to implement SiPMs with small micro-cells [6].

Afterpulsing is due to the carriers trapped in silicon defects during the avalanche multiplication that are released later on during the recharge phase of the GM-APD.

The net effect is that we observed a new current pulse on the tail of the original pulse, see Figure 10.

AP probability increases more than linearly with the overvoltage and quadratically with the cell size because of the corresponding increase in the gain. Optical crosstalk involves

photons emitted during avalanche multiplication and that are re-absorbed in neighboring cells or even in the inactive region of the same cell and causing additional current pulses. Direct-OC occurs when an emitted photon reaches the active region of another cell triggering an additional avalanche practically at the same instant of the original avalanche (consider the speed of light in silicon and the very rapid avalanche ignition in GM-APDs). The result is the double pulse in Figure 11.

Delayed-OC involves, instead, photons that are re-absorbed in the inactive regions of the SiPM. The generated electron (or hole) must then diffuse to the active region of a cell before being able to trigger an avalanche. The correlated pulse has therefore a certain time-delay (in the order of few ns) with respect to the original one, see the third signal in Figure 11.

As for AP, in first approximation OP probability increases more than linearly with the overvoltage and quadratically with the cell size. For a more exhaustive treatment of optical crosstalk in SiPMs refer to [7].

The effect of both AP and OC is to produce additional charge with respect to the charge

associated to an original SiPM pulse (photon-event or a dark-event). The SiPM dark current (reverse bias IV characteristics, $V_{ov} > 0$) is given by the charge due to primary dark pulses plus the charge due to AP and OC pulses. If we assume no AP and no OC then the SiPM dark current at a given V_{ov} consists of the charge due to primary dark pulses only:

$$I_{\text{dark_ideal}}(V_{ov}) = q \times \text{GAIN}(V_{ov}) \times \text{DCR}(V_{ov})$$

This is an “ideal” current since in practice there is always a contribution due to AP and OC events. The contribution of AP and OC to the SiPM dark current can be modeled with an additional term to the ideal SiPM dark current called excess charge factor (ECF):

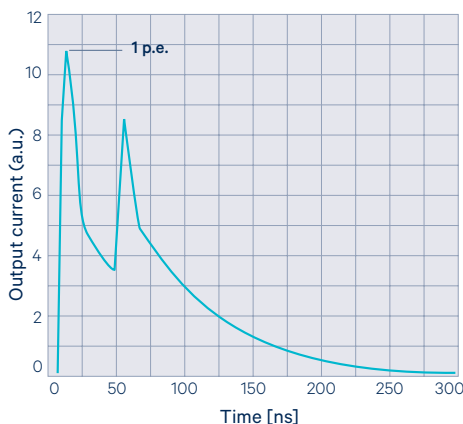
$$I_{\text{dark_real}}(V_{ov}) = q \times \text{GAIN}(V_{ov}) \times \text{DCR}(V_{ov}) \times \text{ECF}$$

Since both $I_{\text{dark_real}}(V_{ov})$ and $\text{DCR}(V_{ov})$ can be accurately measured in laboratory, it is possible to quantify the ECF as

$$\text{ECF}(V_{ov}) = I_{\text{dark_real}}(V_{ov}) / I_{\text{dark_ideal}}(V_{ov})$$

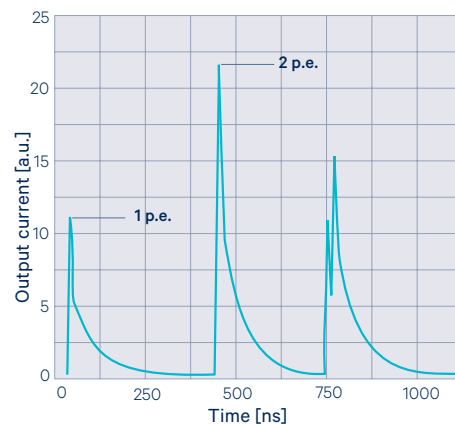
Figure 12 reports a typical plot of the ECF as a function of the overvoltage. By definition, in absence of AP and OC, ECF is one. At low overvoltage, AP and OC probabilities are very low and ECF is closed to 1.

Figure 10



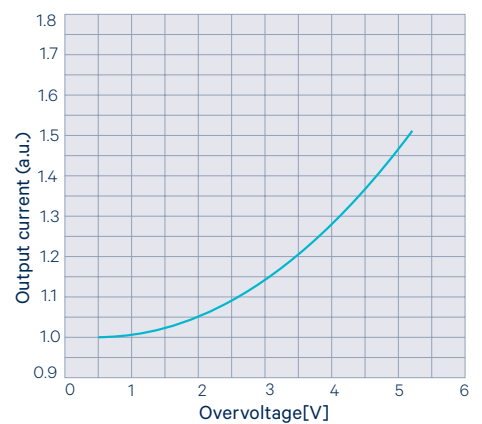
Afterpulsing in SiPMs. The same micro-cell fires again during the recharge phase due to a carrier being released from a previously filled silicon trap. Note that the amplitude of the afterpulse is < 1 p.e. since Cd has not recharged to V_{bias} yet when AP occurs.

Figure 11



Optical crosstalk in SiPMs. From left to right: a single-cell signal (1 p.e.), a direct crosstalk signal (2 p.e.; two cells firing at the same time), and a delayed crosstalk (a second cell fires a few nano seconds after the first one).

Figure 12



The excess charge factor (ECF) in SiPMs accounts for the correlated noise (afterpulsing and crosstalk). Its dependence on the overvoltage reflects the compound AP+OC probability dependence on the overvoltage.

Introduction to silicon photomultipliers (SiPMs)

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