IDQ

SWISS QUANTUM

Redefining Measurement

SINGLE-PHOTON SYSTEMS OVERVIEW

Photon Counting for Brainies

General overview on InGaAs/InP, APD-based photon counting at telecomwavelengths. In common language, telecom wavelengths are mainly the O band, centered around 1310nm (1260 to 1360 nm) and the C band, centered around 1550nm (1530 to 1565 nm) where the fibre attenuation is the lowest. InGaAs/InP, APD-based photon counters have a spectral range from 900nm to 1’700nm and therefore are also used in other applications than telecom.

Whereas the principles of photon counting at visible wavelengths (VIS) are similar, the performances are very different. Values for VIS photon counters are given in chapter 9 and 10 of this document.

29th July 2019

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1. Avalanche photodiodes

The main component of a photon counter is the avalanche photodiode.

In electronics, a **diode** is a two-terminal electronic component with an asymmetric transfer characteristic, with low (ideally zero) resistance to current flow in one direction, and high (ideally infinite) resistance in the other. A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a p-n junction connected to two electrical terminals. The most common function of a diode is to allow an electric current to pass in one direction (called the diode's forward direction), while blocking current in the opposite direction (the reverse direction).

A **photodiode** is a type of photodetector capable of converting light into either current or voltage, depending upon the mode of operation. Photodiodes are similar to regular semiconductor diodes except that they may be either exposed or packaged with a window or optical fiber connection to allow light to reach the sensitive part of the device. Many diodes designed for use specifically as a photodiode use a PIN junction rather than a p-n junction, to increase the speed of response. A photodiode is designed to operate in reverse bias.

An **avalanche photodiode (APD)** is a highly sensitive semiconductor electronic device that exploits the photoelectric effect (Figure 1) to convert light to electricity. APDs can be thought of as photodetectors that provide a built-in first stage of gain through avalanche multiplication. By applying a high reverse bias voltage, APDs show an internal current gain effect due to impact ionization (avalanche effect). In general, the higher the reverse voltage the higher the gain.

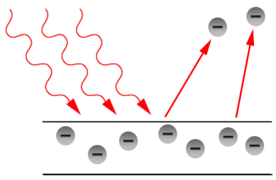


Figure 1

For APDs the reverse voltage is always below the breakdown voltage and APDs are not sensitive enough to detect single photon. The breakdown voltage of a diode is the minimum reverse voltage to make the diode conduct in reverse.

Single-Photon Avalanche Diode (SPAD) (also known as a Geiger-mode APD, photon counters, SPADs or single-photon detectors) are a class of solid-state photodetectors with a reversely biased p-n junction in which a photo-generated carrier can trigger an avalanche current due to the impact ionization mechanism. SPADs are able to detect low intensity signals (down to single photons). The fundamental difference between a SPAD and an APD is that SPADs are specifically designed to operate with a reverse bias voltage well above the breakdown voltage (on the contrary APDs operate at a bias voltage less than the breakdown voltage). This kind of operation is also called Geiger mode in literature, for the analogy with the Geiger counter.

2. Principle of photon counting

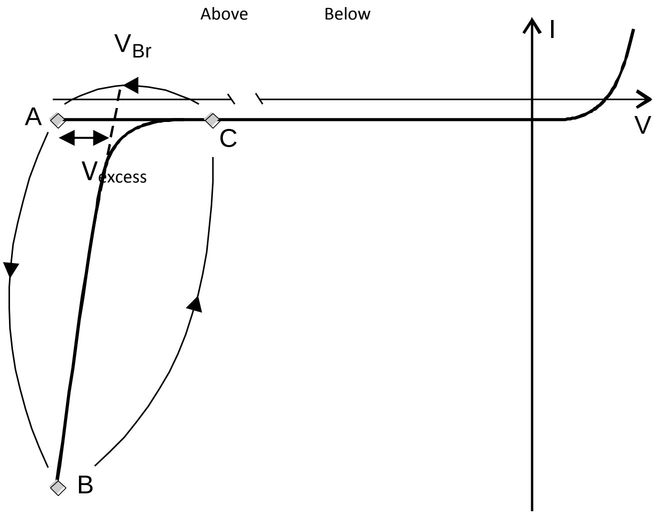


Figure 2

Figure 2 represents the I-V (current–voltage) characteristics of an APD and illustrates how single-photon sensitivity can be achieved. This mode is also known as Geiger mode. The APD is biased, with an excess bias voltage, above the breakdown value V_{Br} and is in a metastable state (point A). It remains in this state until a primary charge carrier is created. In this case, the amplification effectively becomes infinite, and even a single-photon absorption causes an avalanche resulting in a macroscopic current pulse (point A to B), which can readily be detected by appropriate electronic circuitry. This circuitry must also limit the value of the current flowing through the device to prevent its destruction and quench the avalanche to reset the device (point B to C). After a certain time, the excess bias voltage is restored (point C to A) and the APD is again ready to detect a single photon. The actual value of the breakdown voltage depends on the semiconductor material, the device structure and the temperature. For InGaAs/InP APDs, it is typically around 50V. The detection efficiency but also the noise of an APD in Geiger mode depends on the excess bias voltage.

3. Terminology and explanations

a) Detection efficiency

The performance of an avalanche photodiode APD in single-photon detection mode is characterized mainly by its detection efficiency. This quantity corresponds to the probability of a photon impinging on the photodiode to be detected. The detection efficiency for an InGaAs SPAD results from two different factors:

- the probability that a photon is absorbed in the InGaAs layer

- the probability that the photo-generated carrier triggers an avalanche when crossing the multiplication zone and generates an electrical current at the output

In a fiber-based photon counter there can be some coupling losses between the fiber and the active area of the photodiode. In order to compensate this, the bias voltage is slightly increased in order to get the same detection efficiency. This slightly increases the dark count rate.

The quantum detection efficiency increases when the excess bias voltage is raised. At 1550 nm, a detection efficiency value as high as 25% is typical, for an InGaAs/InP photodiode. Generally for InGaAs/InP photon counting modules the detection efficiency is adjustable.

Detection efficiency, quantum detection efficiency and detection probability are to be considered as synonyms in this document.

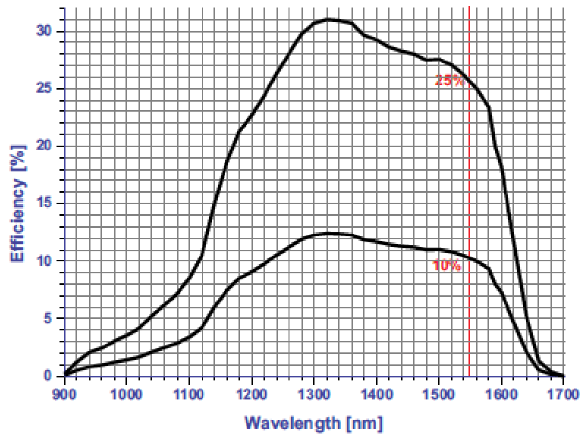


Figure 3: Typical spectral response of an InGaAs/InP photodiode

b) Dark counts

In a SAPD, avalanches are not only caused by the absorption of a photon, but can also be randomly triggered by carriers generated in thermal, tunnelling or trapping processes taking place in the junction. They cause self triggering effects called dark counts.

The easiest way to reduce dark counts is to cool the detector. This reduces the occurrence of thermally generated carriers. At low temperature, dark counts are thus dominated by carriers generated by band to band tunneling and more importantly trapped charges (see below c)). Raising the excess bias voltage increases the occurrence of dark counts, increases the detection efficiency and decreases the timing jitter. The operation point, in terms of bias voltage, must thus carefully be selected.
In gated mode, one typically quantifies this effect as a dark count probability per nanosecond of gate duration.
Example: Dark counts in [Hz]: 1’350 counts gate width: 20 [ns] trigger rate: 10 [MHz]
Dark counts in ns of gate = 1’350 / (20 x 10’000’000) = 6.75E-06

c) Afterpulses

Perhaps the major problem limiting the performance of present InGaAs/InP APDs is the enhancing of the dark count rate by so-called afterpulses.

This spurious effect arises from the trapping of charge carriers during an avalanche by trap levels inside the high field region of the junction, where impact ionization occurs. When subsequently released, these trapped carriers can trigger a so-called afterpulse. The lifetime of the trapped charges is typically a few µs for InGaAs/InP APDs. The probability of these events is also proportional to the number of filled traps, which is in turn proportional to the charge crossing the junction in an avalanche before the quenching takes place. The total charge can be limited by ensuring prompt quenching of the avalanches.

It is also important to note that reducing the operation temperature of the APD increases the lifetime of the trapped charges. The cooling temperature must thus carefully be chosen to minimize the total dark count probability (including afterpulses). The optimal temperature is typically around 220 K for current InGaAs/InP SPADs.

So far, the technique to reduce the dark count enhancement by afterpulses has been to use a deadtime. If following a detection event the voltage across the SPAD is kept below the breakdown voltage for a time interval longer than the trap lifetime, the trap levels are empty and cannot trigger an avalanche. Typical trapping times are in the µs range for InGaAs/InP SPADs. Using a deadtime (=time during which the voltage is not raised above breakdown) to inhibit gates for a time that is long compared to the trapped charges lifetime after each avalanche proves to be useful. At a trigger rate of 100MHz, the time interval between 2 gates is 10ns. Thus, a deadtime of 1us will inhibit the next 100 gates and the maximum counting rate will be limited at 1 MHz. This is valid in gated mode (see page 7/12). In free-running mode, the deadtime will also limit the count rate After the deadtime ends, you will be able to detect photons for an unlimited period of time until a primary charge carrier is created.

d) Timing resolution

For many applications, the timing resolution, or jitter, of the detector is also important. The jitter is the undesired deviation from true periodicity of an assumed periodic signal. In this context, it is the time variation of the electric output signal of the detector for a periodically arriving light signal. The timing performance typically improves with an increase of the excess bias voltage. In order to quantify it, one sends short and weak light pulses to the detector. The spread of the onset of the avalanche pulses is then monitored with a time-to-digital converter. At a 30% detection efficiency, a timing resolution of about 115 ps FWHM is typical for InGaAs/InP SPADs.

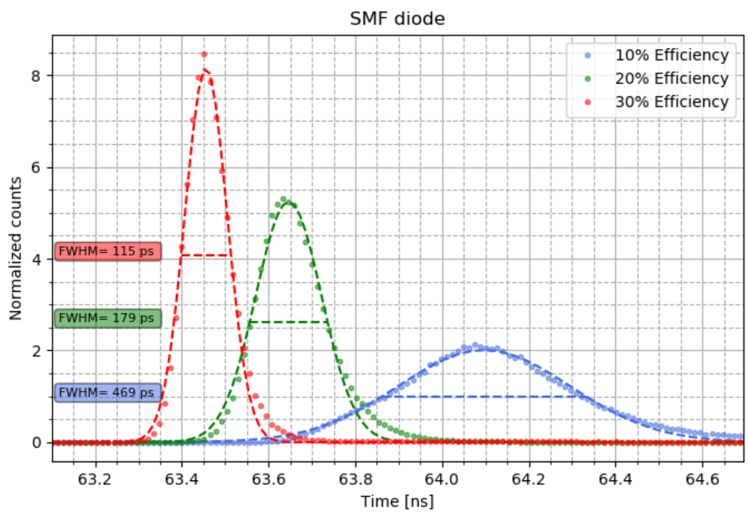


Figure 4: Timing jitter measurement on the InGaAs/InP ID221 & ID230 device (SMF fibred)

4. Analog versus Geiger mode

Avalanche mode (linear modes)

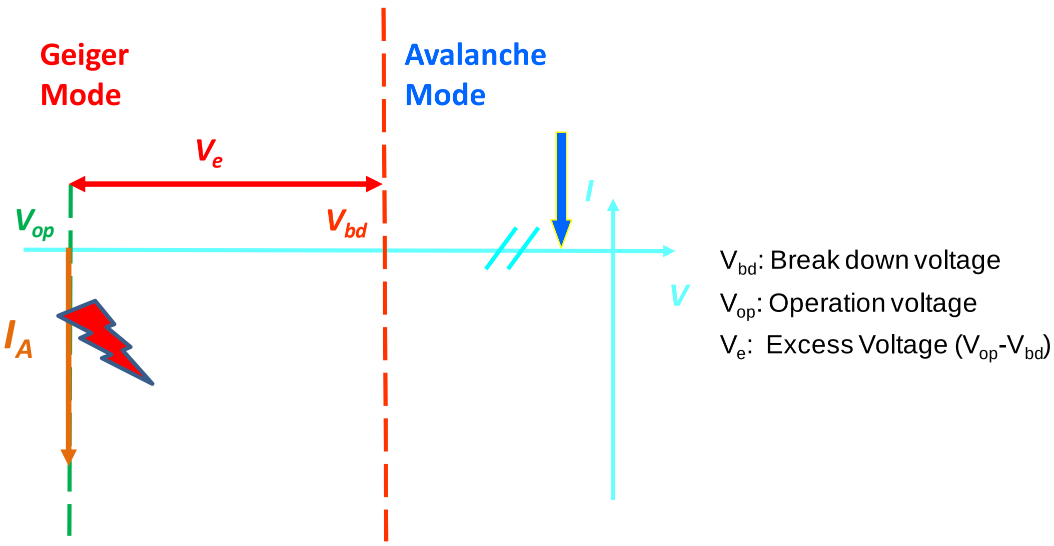
Avalanche photodiodes (APDs) are working in so-called **analog mode**. This means the **bias**-voltage applied on the diode is **always below breakdown** voltage. The output **signal is proportional to** the incoming light **intensity**. APDs in analog mode are **NOT sensitive enough** to detect **single** photons.

Single photon avalanche mode (Geiger mode)

Our products ID100, ID120, ID210, ID221 and ID230 are SPADs (=Single Photon Avalanche Diodes) based modules. SPADs (Single Photon Avalanche Diodes) also called **photon counters.** They are working in **digital mode**, also called **Geiger mode**. This means the **bias**-voltage applied on the diode is **above breakdown**.

When a **photon** is detected it **creates an avalanche** which has to be quenched, which means the bias-voltage is brought below breakdown in order to **stop (quench) the avalanche** and **then** brought back **above breakdown to make it sensitive again**.

The detector is **only sensitive when** the bias voltage is above break down. The output signal **is NOT proportional** to the incoming light intensity. SPADs are **sensitive enough** to detect **single** photons!



Single-**P**hoton **A**valanche **D**iode

- Bias: well ABOVE breakdown
- Infinite gain
- Geiger-mode: it's a TRIGGER device!!
- Avalanche quenching is required

Avalanche **P**hoto **D**iode

- Bias: slightly BELOW breakdown
- Gain: limited < 1'000
- Linear-mode: it's an AMPLIFIER

Figure 5: Avalanche mode (linear) vs single photon avalanche mode

5. Free running versus gated mode

Free running mode

Only after an avalanche the bias voltage is for a very short time brought below break down, called dead time, in order to quench the avalanche. At all other times, the bias voltage is above breakdown, and the SPAD state is ON.

When an avalanche occurs in the SPAD after detection of a photon or a dark count, it is sensed by the capture electronics. A pulse is produced on the detection output of the device and the quenching electronics stops the avalanche. In order to limit afterpulsing, the SPAD bias voltage is maintained below breakdown (SPAD state is OFF) until the end of the dead time.

The free-running mode is very convenient for applications where the photon arrival time is unknown.

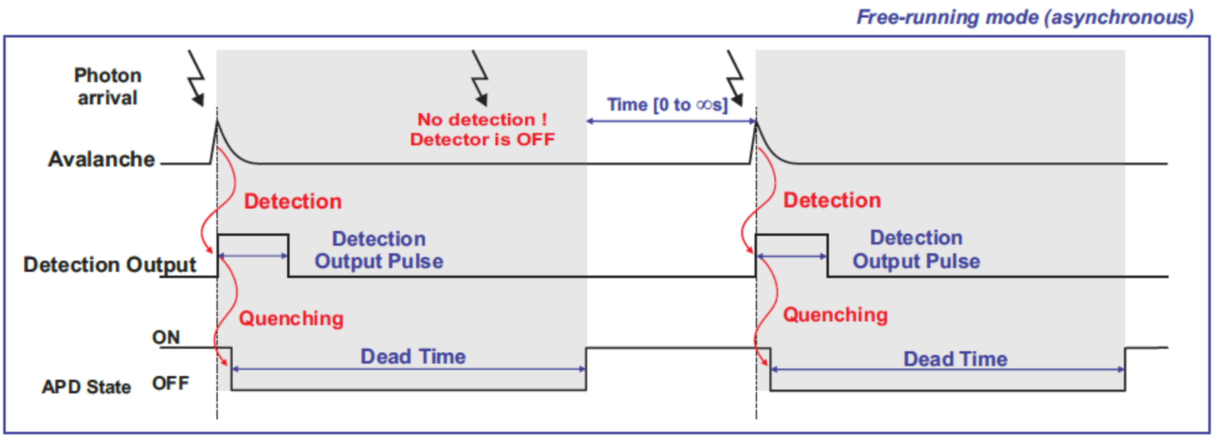


Figure 6: Free-running mode description

The deadtime can be set by the user for InGaAs/InP devices:

- ID210 from 0.1us to 100us
- ID221 from 1us to 25us
- ID230 from 2us to 100us

Gated mode

In order to reduce the dark count rate, the SPAD can be biased above breakdown voltage only during a short period of time. This period of time (=duration) is called the gate and is adjustable in width and frequency with an external or internal trigger.
The detector is only sensitive during the gates. So, the gated mode is used for applications where the photon arrival time is known. This mode significantly reduces the dark count rate.
A photon won't be detected if the gate is not open OR if a deadtime is applied (after a previous detection).
When an avalanche occurs within the gate because of a detection of a photon or a dark count, a pulse is output at the detection connector. The quenching electronics closes the gate and a dead time can be applied, resulting in one or more blanked pulses.

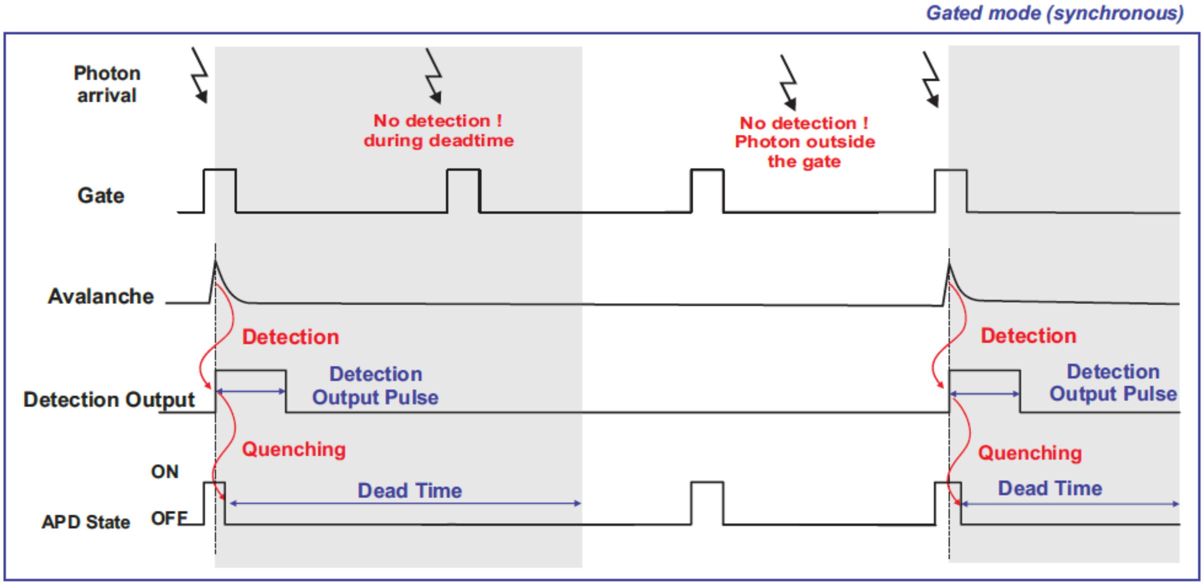


Figure 7: Gated mode description

Free running versus gated mode

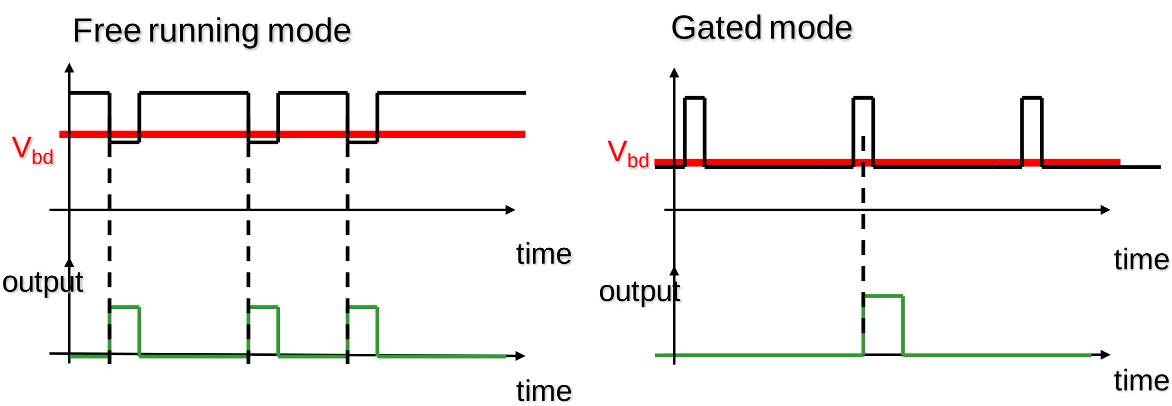


Figure 8: Free running versus gated mode

6. Reduction of afterpulsing using the deadtime

The deadtime is applied after each detection (real or dark count). If the voltage across the SPAD is kept below the breakdown voltage for a sufficiently long time interval, i.e. longer than the trap lifetime, trap levels are empty and cannot trigger an avalanche. The typical trapping time is in the µs range for InGaAs/InP SPADs.

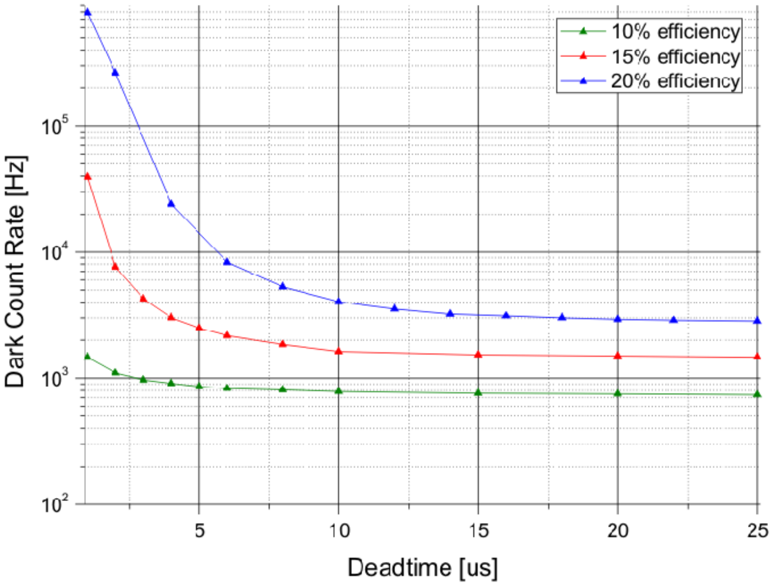


Figure 9: Typical DCR vs deadtime at 10%, 15% and 20% detection efficiencies for the ID221 photon counter

When a photon arrives on the InGaAs/InP photodiode and creates an avalanche, a deadtime has to be applied after the quenching (stopping the avalanche). Thanks to the deadtime (time during which no voltage is applied on the photodiode), the number of carriers and holes decreases significantly and so it avoids a high afterpulsing probability: if too many carriers are trapped in the photodiode, when the next gate will be open or when the deadtime ends, a new avalanche might occur and you will have a count which is an afterpulse (=”noise”).

If you use a short deadtime (or no deadtime), you will have a large number of afterpulses. You may then get the impression that you have a high count rate and a high quantum efficiency, but this is just noise.

Please see figure 10, the shape of the curves “Count rate vs trigger rate” with different deadtimes. You clearly see the impact of deadtime on afterpulsing rate. As an example, a 5µs deadtime has a significant effect on the afterpulsing rate when the trigger rate is higher than 1MHz. Please note that the deadtime reduces the afterpulsing rate but also the number of detections coming from light.

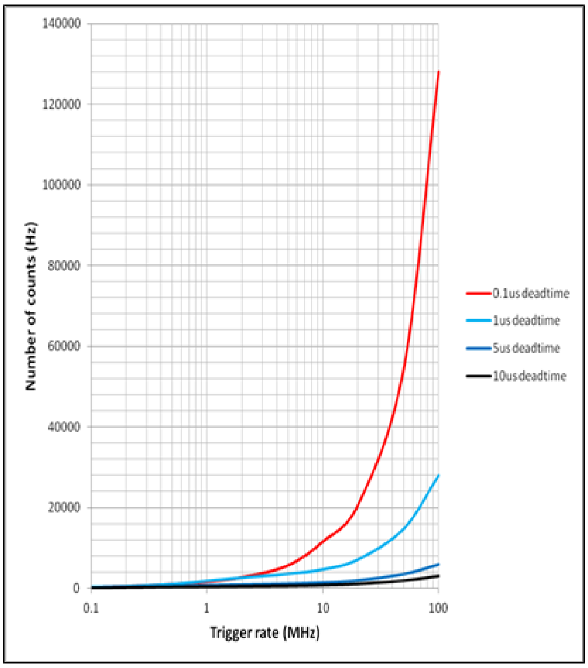


Figure 10 : Number of counts vs trigger frequency depending on the deadtime in gated mode for the ID210 photon counter

7. Nominal versus Effective Gate width

In the timing diagram below, a realistic chronogram is shown taking into account the slew rates of the different electronic stages (the transit times in the electronic stages are assumed to be negligible). One can note that the gate control signal width differs from the gate output signal width. More important, the gate control signal width (the width applied by the user) is larger than the effective gate width. The difference between the applied and the actual gate width decreases when the excess voltage, i.e. the efficiency, is raised. Note that this effect can also be seen by building an histogram in memory of the dark counts using a time-to-digital converter.

From this simplified explanation we can conclude that:

- a difference exists between the gate width applied by the user and the effective gate width,

- a setting of a small gate width may result in a lower peak efficiency than that of the current set level, or result in no efficiency at all (possible at low excess bias voltage),

- the dark count rate specified for the ID210 is fairly evaluated with a measured FWHM effective gate width of 1ns. One has to be aware that a dark count rate expressed per ns of the gate control signal width would be significantly underestimated in case of a gate control signal width much larger than the effective gate width.

Note finally that the shrinkage of the effective gate width also finds its explanation in the avalanche current build up duration.

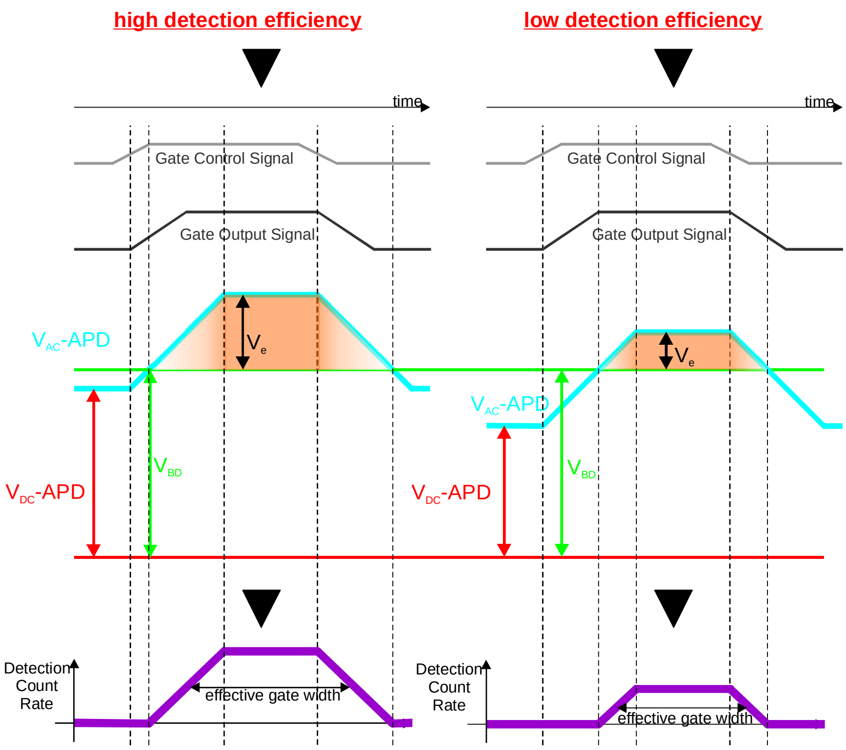


Figure 11 : Nominal versus Effective Gate width

8. Linearity of Detection Probability

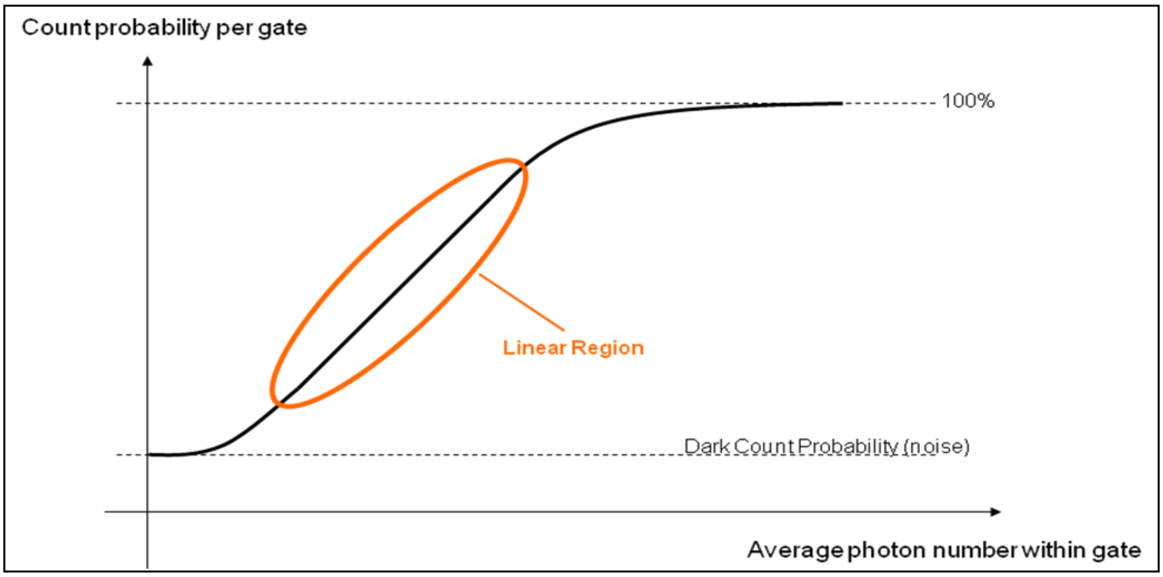


Figure 12 : Linearity of Detection Probability

Gated mode

When using a photon counter, you can easily saturate the device:

- If you use a laser source sending on average 2 photons per pulse you will have a count rate twice as high as if you would send on average one photon per pulse; this what is called linearity of the photon counters.
- If no optical signal is sent on the SPAD, then the detection rate would be your dark count rate.

Between the saturation region and the dark count rate region, your detector is "linear": the count rate of the detector is proportional to the number of photons arriving on the SPAD. Attention: this is valid only if a deadtime is applied (cf chapter 6 " Reduction of afterpulsing using the deadtime").

Free-running mode

This will be very similar to gated mode except that the saturation region is defined by your deadtime: For a 5us deadtime, the maximum count rate is 1/5us = 200kHz => saturation.

9. Photon counting at VIS wavelength

Silicon devices (for visible wavelength 350-900nm) does normally not have an adjustable quantum efficiency.

For example, the deadtime is 45ns for the silicon photon counter ID100 and it is NOT adjustable.

For silicon devices, the trapping time is in the range of a few tens of nanoseconds and the afterpulsing probability is low.

Silicon devices have a lower jitter, as low as 45ps for the ID100, and usually work in free running mode only.

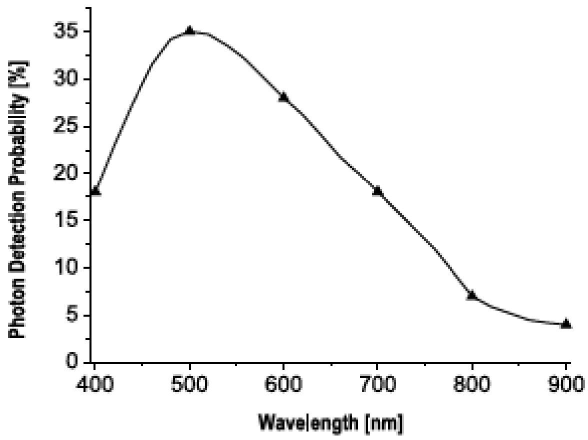


Figure 13 : Detection efficiency for silicon based photon counter

10. Our Single-Photon Detectors

<u>Visible Photon Counters</u>
Silicon Avalanche Photodiode

ID100 [350-900 nm]	**ID120** [350-1000 nm]	**ID281** [400-2500 nm]
		
35% Quantum Efficiency	80% Quantum Efficiency	0.8K Closed-Cycle Cryostat
40 ps Timing Resolution	500 µm Active Area	85% Quantum Efficiency
Low Dark Count Rate (5 Hz)	Free-Running	30 ps Timing Resolution

Infrared Photon Counters

InGaAs/InP and SNSPD

ID281 [400-2500 nm]	**ID230** [900-1700 nm]	**ID221** [900-1700 nm]
		
0.8K Closed-Cycle Cryostat	25% Quantum Efficiency	20% Quantum Efficiency
85% Quantum Efficiency	150 ps Timing Resolution	150 ps Timing Resolution
30 ps Timing Resolution	Low Dark Count Rate (50 Hz)	Low Dark Count Rate (800 Hz)

11. Other Products

Timing & Counting Electronics

Intelligent Time Controller

ID900 Time Controller

Time-tagging and histogramming
Picosecond timing
Conditional programmable outputs

<u>From our labs</u>

QKD & Laser Source

Clavis^3 QKD	ID300 Lase Source
	
Open QKD platform for R&D applications	Wavelength 1550nm
High-Speed Key Generation	300 ps Laser Pulses
Secure Key Exchange up to 100km	0 to 500 MHz Repetition Rate

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