# COURSE OUTLINE

- Introduction
- Signals and Noise
- Filtering
- Sensors: PD6 – Single-Photon Avalanche Diodes

# APDs for Single-Photon Counting (SPC)?

**APDs can detect smaller optical pulses than PIN diodes**, thanks to the internal gain M.

However, the improvement of sensitivity is much **lower than that brought by PMTs** with respect to vacuum tube PDs. The reason is that in comparison to PMTs the APD gain M has

1. much **lower mean value $\overline{M}$**
2. **much stronger statistical fluctuations**, with relative variance that increases with $\overline{M}$

The **QUESTION** arises:

can we employ linear amplifying APDs instead of PMTs in single photon counting and timing techniques?

And the **ANSWER** is: **NO**!

More precisely, **almost NO for silicon APDs** and **absolutely NO for APDs in other materials**. In fact, we will now verify that only some special Si-APDs achieve single photon detection, although with marginal performance (detection efficiency lower than APD in analog detection; etc.), and other APD devices are out of the question.

# APDs for SPC ?

- The APD output pulses due to a single primary carrier (single-photon pulses) are observed and processed accompanied by the noise of electronic circuitry, arising in the preamplifier.
- A pulse comparator is employed to discriminate SP pulses from noise; pulses higher than the comparator threshold are accepted, lower pulses are discarded.
- The parameters of the set-up (rms noise; pulse amplitude; threshold level) should be ajusted to provide:
    1. Efficient **rejection of noise**, i.e. low probability of false detections due to the noise
    2. Efficient **detection of photon pulses**, i.e. high probability of detecting the SP pulses, which have variable amplitude with ample statistical fluctuations

# Noise Rejection in Photon Counting

- With noise amplitude having gaussian distribution (most frequent case) with variance $\sigma_n$, the **noise rejection threshold level must be at least** $\boldsymbol{N_{nr} \geq 2{,}5\, \sigma_n}$ , in order to keep below <1% the probability of false detection
- We have seen that by employing an **optimum filter** for measuring the amplitude of detector pulses we get rms noise (in number of electrons)

$$\sigma_n = \frac{\sqrt{2C_L\sqrt{S_v}\sqrt{S_i}}}{e}$$

e =electron charge and typically:
$C_L \approx$ 0,1 to 2pF load capacitance;
$\sqrt{S_v} \approx$ 2 to 5nV $\mathrm{Hz}^{-1/2}$ series noise;
$\sqrt{S_i} \approx$0,01 to 0,1 pA $\mathrm{Hz}^{-1/2}$ parallel noise

With high quality APD and preamp we get typically $\sigma_n \approx$ 40 to 120 electrons.
The noise rejection threshold required then is

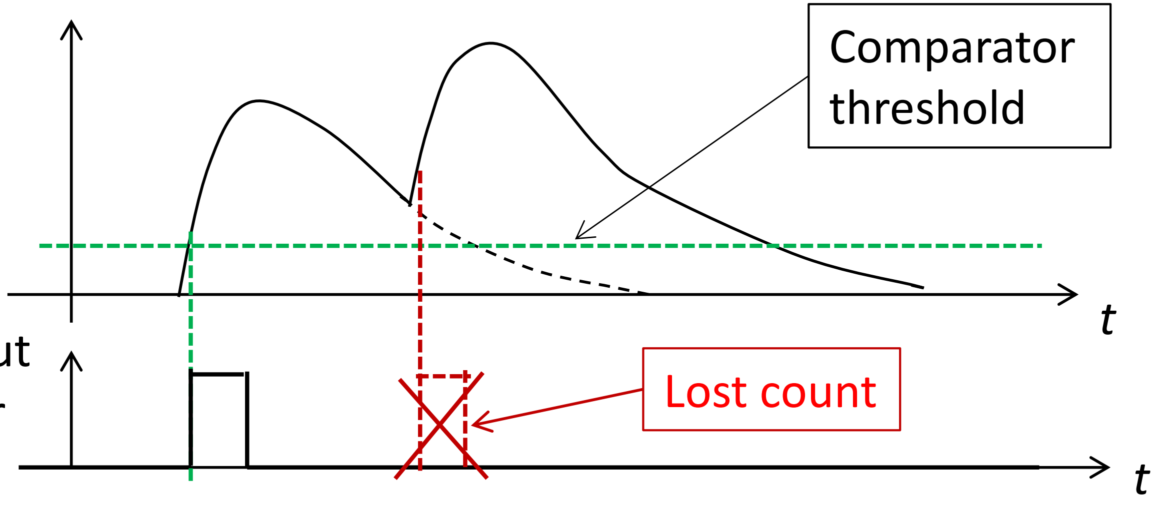
$$N_{nr} \geq 2{,}5\ \sigma_n \approx 100 \text{ to } 300 \text{ electrons.}$$

Furthermore, M just higher than $N_{nr}$ is not sufficient for having SP pulses higher than the threshold: we will see that **M much higher than $\boldsymbol{N_{nr}}$ is necessary**.

- We know that the optimum filter (and of course also an approximate optimum) is a low-pass filter and the output pulse has a width of some noise corner time constant $T_{nc}$ . Since in our case $T_{nc}$ ranges from 10ns to a few 100ns, the output pulses are fairly long and this brings drawbacks.

# Count losses in Photon Counting

- In photon counting **the finite width of the SP pulse causes count losses**. When the time interval between two photons is shorter than the output pulse width, pulse pile-up occurs (i.e. the two pulses overlap), the comparator is triggered only once and one count is recorded instead of two



SP pulses output of an approx. optimum filter

Comparator output fed to the counter

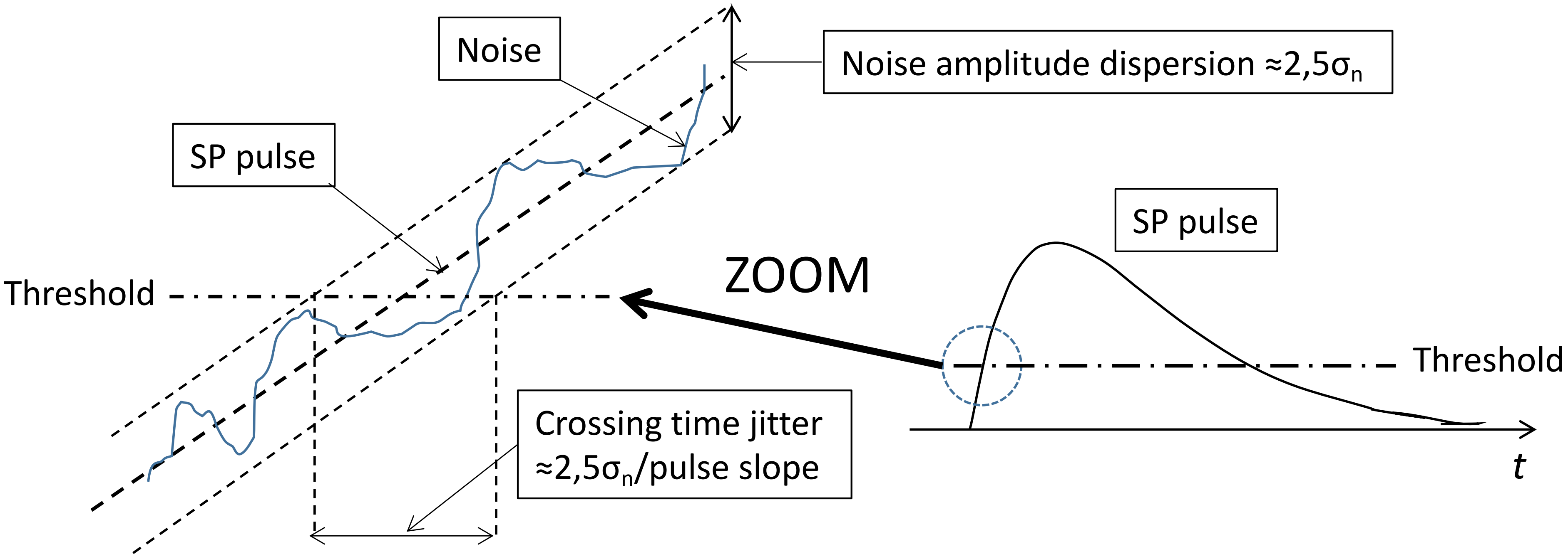
Comparator threshold

Lost count

- Photons occur randomly in time, hence the probability of pulse **pile-up** increases when the pulse width is increased.
- In conclusion, **the percentage of lost counts increases as the pulse-width is increased**. The width of the SP pulses should be minimized, in order to achieve efficient photon-counting with minimal percentage of lost counts.

# Time-jitter in Photon Timing

- In photon timing, the arrival time of the pulse is marked by the **crossing time of the threshold** of a suitable circuit by the SP pulse.
- The noise causes **time jitter** (statistical dispersion) of the threshold crossing time
- A quantitative analysis is not reported here, but it is evident that the time jitter is proportional to the noise and **inversely proportional to the pulse rise slope**.
- A fairly **long $T_{nc}$** implies reduced pulse bandwidth and reduced slope of the pulse rise, hence **wide time jitter**.



# Photon Counting with wide-band electronics

For reducing count-losses and time jitter, we must process the APD pulses with filter bandwidth wider than the optimum filter. However, this implies higher noise, hence higher threshold level and higher gain required to the APD.

# Efficiency in the detection of SP pulses

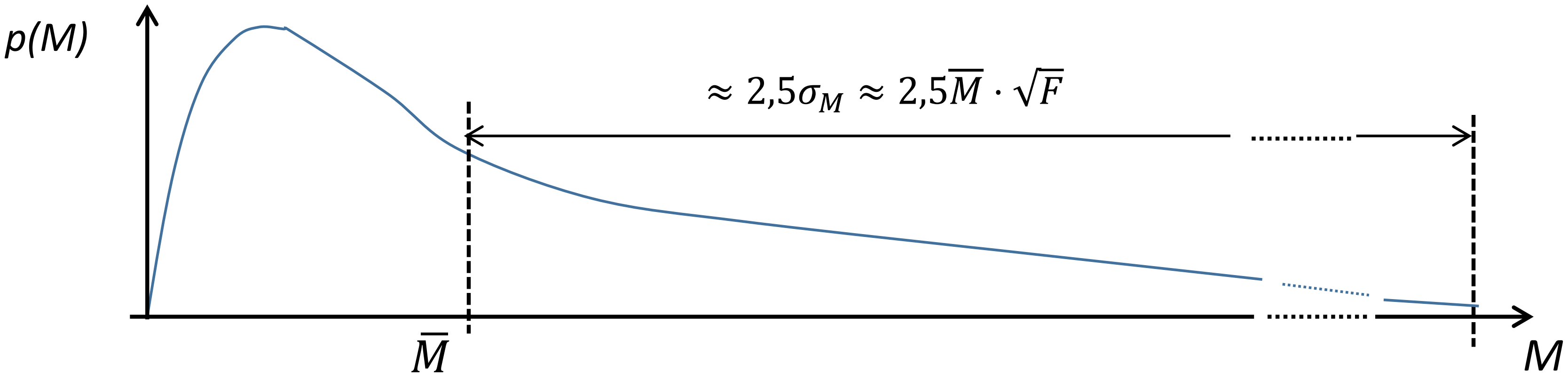
- If the APD gain M were constant for all SP pulses, it would be sufficient to have M just higher than the noise rejection threshold level $\boldsymbol{N_{nr}}$ , but this is not the case.
- The gain **M has strong statistical fluctuations**, hence a high excess noise factor F>>1, which is directly related to the relative variance of M

$$F = 1 + v_M^2 = \frac{1 + \sigma_M^2}{\left(\overline{M}\right)^2}$$

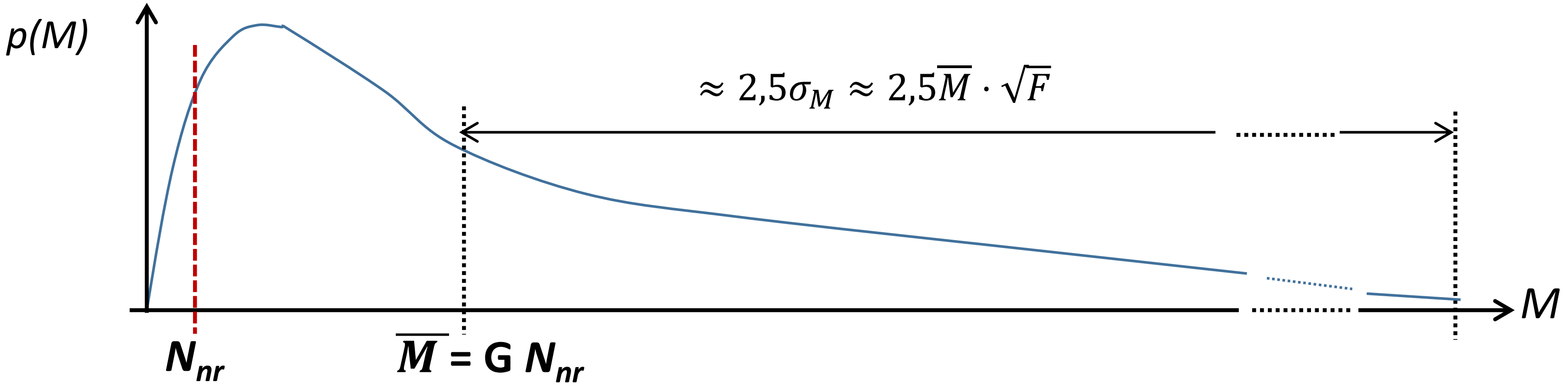
- The statistical M distribution thus has variance **$\boldsymbol{\sigma_M}$ remarkably greater than the mean value $\boldsymbol{\overline{M}}$**

$$\sigma_M = \overline{M}\sqrt{F-1} \approx \overline{M} \cdot \sqrt{F}$$

- **M has a strongly asymmetrical statistical distribution**, with most of its area below the mean value $\overline{M}$ and a long “tail” above it



# Efficiency in the detection of SP pulses



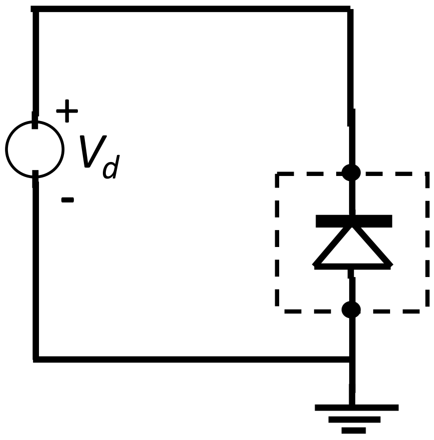
- Therefore, **with a mean gain $\overline{M}$ just above the noise rejection threshold a major percentage of the SP pulses is rejected**. This downgrades the photon detection efficiency, i.e. the basic performance of the detector.
- In order to limit the reduction of detection efficiency due to the threshold, the mean gain **$\overline{M}$ should be higher than the noise rejection threshold** $N_{nr}$ by a factor G>>1
- In the most favorable case (special Si-APD with optimum filtering), the value of $\overline{M}$ necessary for attaining the noise rejection threshold $N_{nr}$ is near to the maximum available APD gain, but there is still some margin. In other cases (regular Si-APDs with wideband electronics) there is no margin at all.
- **CONCLUSION:** photon counting with linear amplifying APDs is possible only with special Si-APDs and with photon detection efficiency strongly reduced with respect to that obtained with the same APDs by measuring the analog current signal.

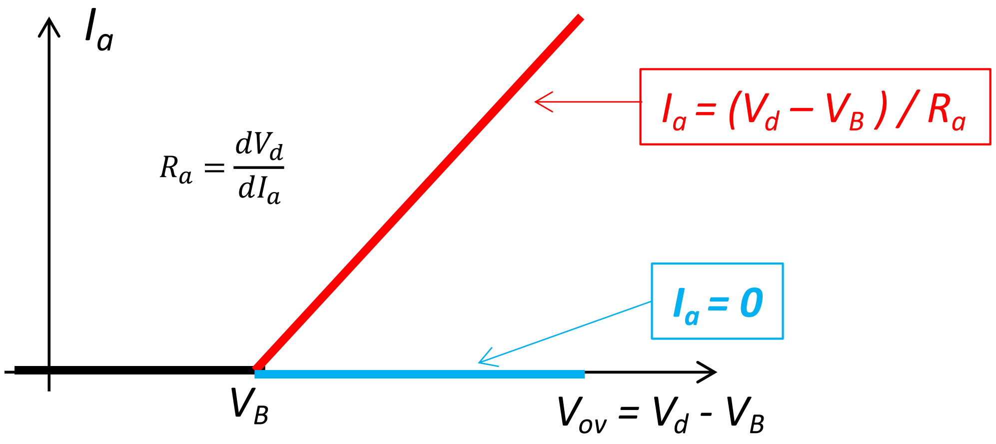
# Avalanche diodes above VB

- We have seen that the **positive feedback inherent in the avalanche multiplication of carriers causes strong limitations** to the internal gain of APDs in linear operation mode, thus ruling out the possibility of employing them instead of PMTs in single photon counting and timing.
- **However, the positive feedback makes possible a radically different operation mode** of some avalanche diodes, which working in this mode at voltage **above** the Breakdown Voltage $V_B$, turn out to be valid single-photon detectors.
- It is called **Geiger-mode operation**
  - Single photon switches on avalanche: macroscopic current flows
  - It’s a triggered-mode avalanche: detector with “BISTABLE inside”
  - Avalanche is quenched by pulling down diode voltage $V_d \approx V_B$ (or below)
  - Diode voltage is then reset above the breakdown

- Such avalanche diodes, operating above the breakdown voltage in Geiger mode, generate macroscopic pulses of diode voltage and current in response to single photons. They are therefore called **Single-Photon Avalanche Diodes (SPADs)**.

# SPAD I-V characteristic above VB





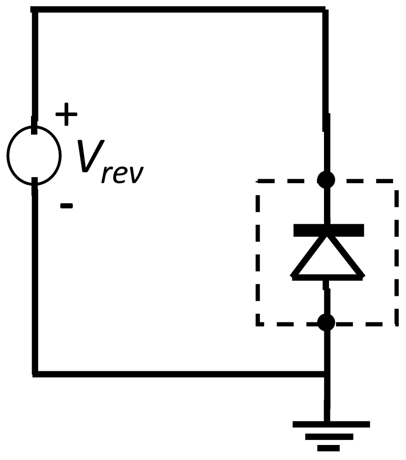
The I-V characteristics shows a **bistable** behavior above breakdown $V_d > V_B$ :

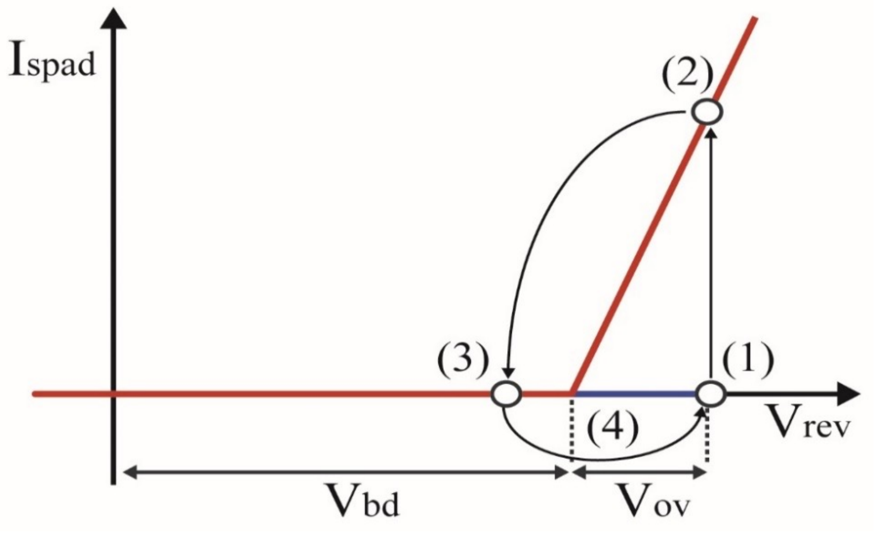
a) Without free carriers in the depletion region, $I_A$ =0 above breakdown

b) at $V_d > V_B$ a self-sustaining avalanche can be **started even by a single free carrier** entering in the high field region at $V_d > V_{B.}$ In this case $I_A$ >0.

The higher the bias voltage above the breakdown, the higher the avalanche current. Therefore, the **$\Delta V = V_d - V_B$** is a key parameter: it is called excess bias or **overvoltage**.

# Geiger mode operation





(1) Quiescent state: Bias voltage $\mathbf{V_{rev}}$ above breakdown $\mathbf{V_{bd}}$ (with excess bias $\mathbf{V_{ov}}$ ) is applied and no current flows

(2) Avalanche current flowing: it is triggered by a photon or noise

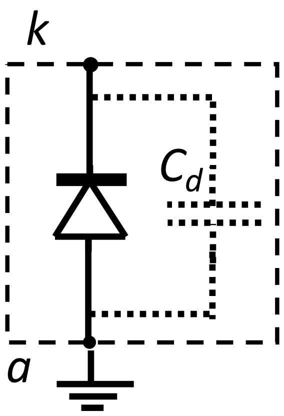
(3) Quenching: bias voltage $\mathbf{V_{rev}}$ is lowered below the breakdown to stop the avalanche current flowing

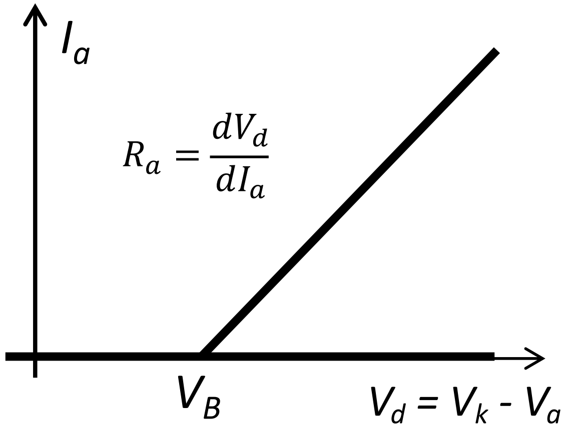
(4) Reset: voltage across the junction is restored to the initial value

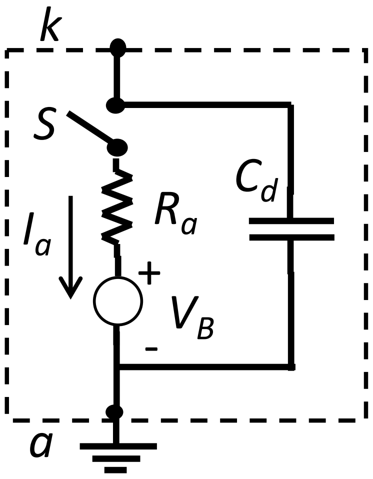
# SPAD main properties

- In order to be able to operate in Geiger mode above the breakdown voltage, a **diode should have uniform properties over the sensitive area**: in particular, it must be **free from defects** causing local field concentration and lower breakdown voltage
- Pulses are produced in SPADs also by the spontaneous thermal generation of single carriers in the diode junction and constitute a **dark count rate (DCR)** similar to that observed in PMTs. **Low DCR is a basic requirement** for an avalanche diode to be employed as SPAD.
- Various parameters characterizing the **detector performance strongly depend on the diode voltage**: probability of avalanche triggering, hence the photon detection efficiency; amplitude of the avalanche current pulse; dark count rate; delay and time-jitter of the electrical pulse with respect to the true arrival time of the photon; etc.
- **The breakdown voltage** depends on the structure of the device and on doping levels. $V_B$ also strongly depends on junction **temperature**. At constant supply voltage $V_d$, the increase of $V_B$ causes a decrease of excess bias voltage $V_{ov}$, impairing detector performance. Junction-temperature stability is very important.

# Equivalent Circuit of Diode above Breakdown





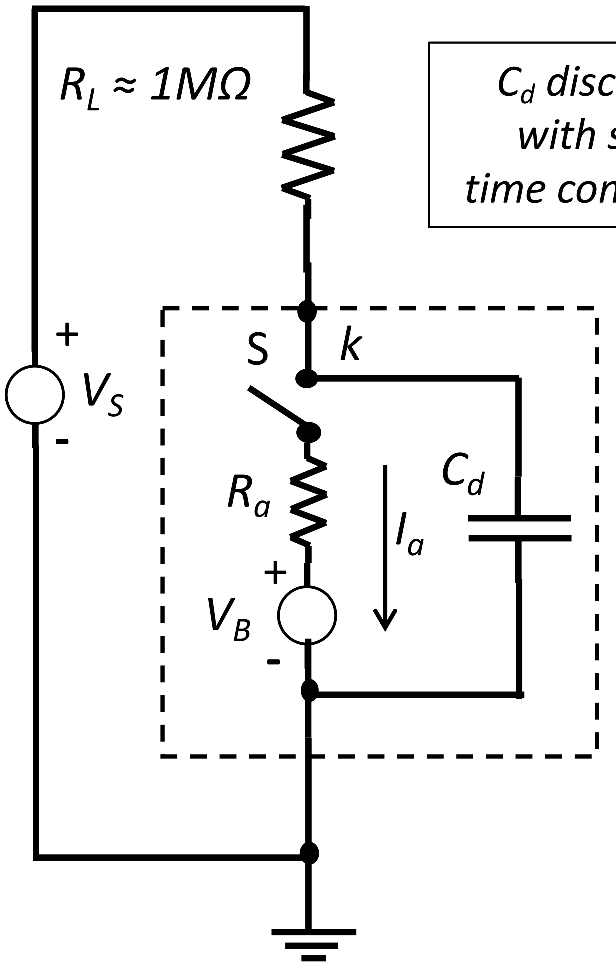


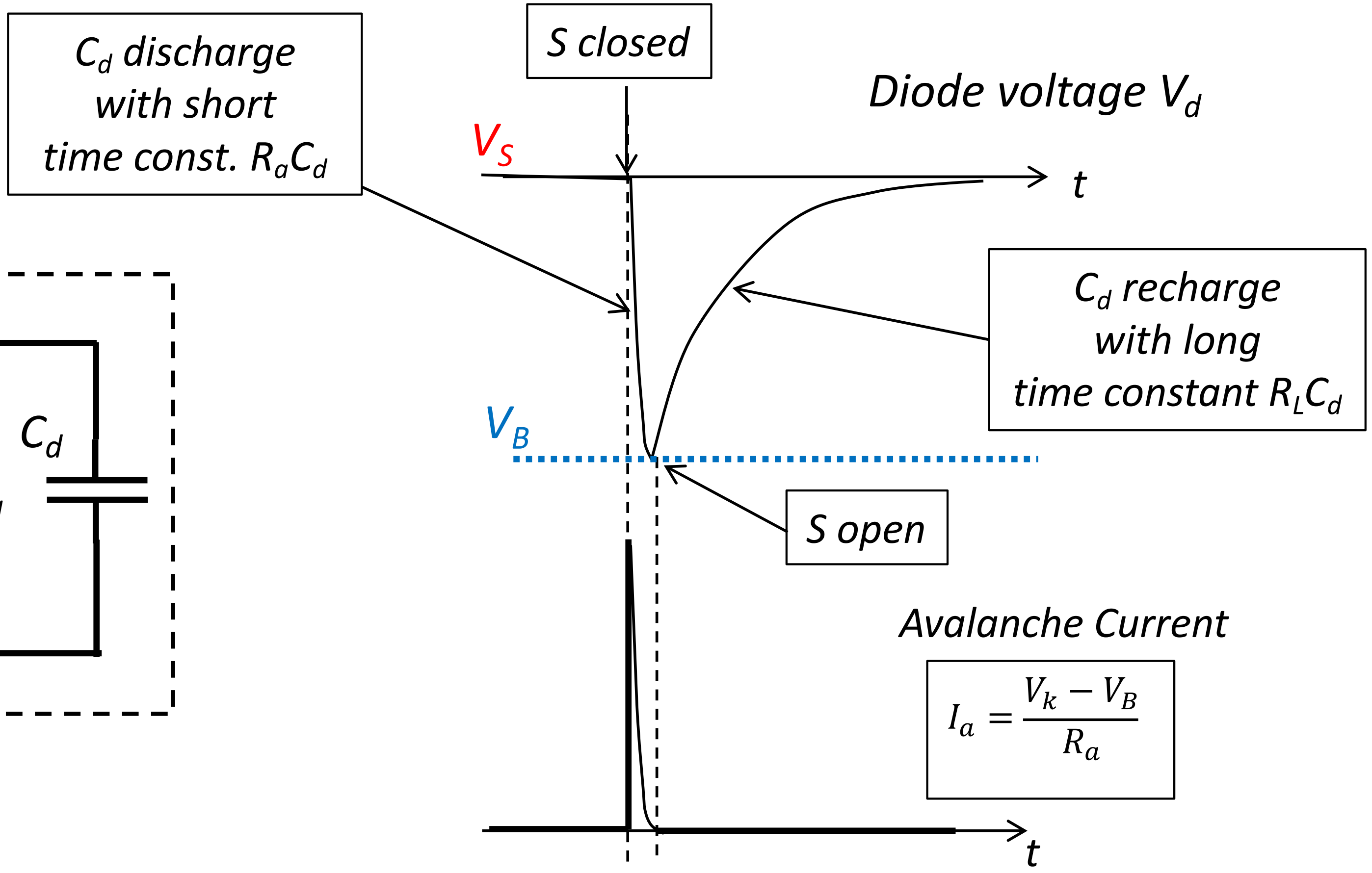
Equivalent Circuit

The equivalent circuit of the diode provides a quantitative understanding of the diode operation and confirms that the pulses observed correspond to single carriers generated in the device, spontaneously or by the absorption of single photons

- at $V_d > V_B$ the switch S can be closed or open; when it is closed, the avalanche current flows. At $V_d \leq V_B$ it is always open.
- **Closing the switch** is the equivalent of **triggering the avalanche** in the diode. Therefore, S is closed when a carrier injected or generated in the high field region succeeds in triggering the avalanche
- S then is open when the avalanche current is quenched (i.e. terminated) by the decrease of the diode voltage down to $\boldsymbol{V_d \approx V_B}$

# Passive Quenching Circuit



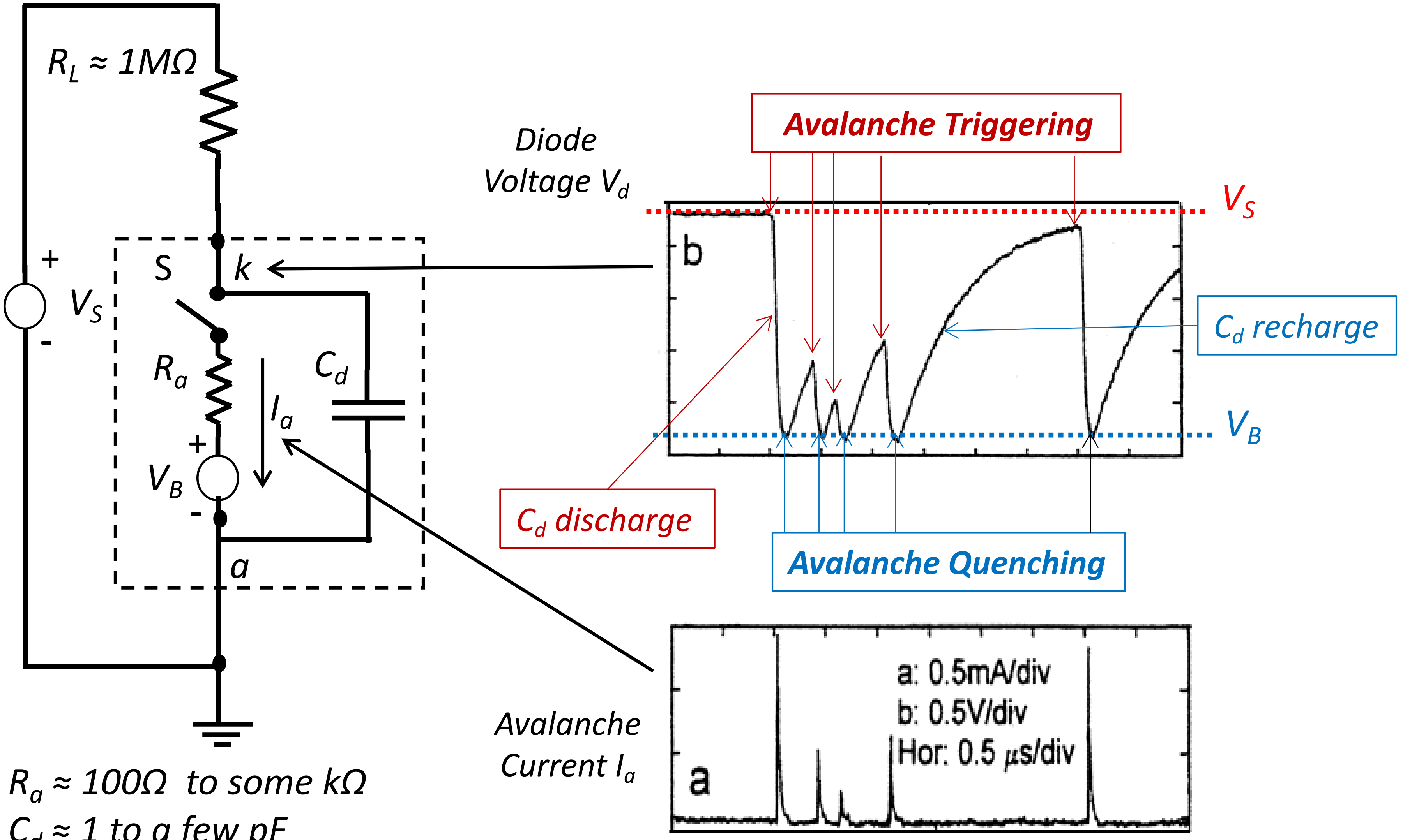


$$I_a = \frac{V_k - V_B}{R_a}$$

$R_a \approx 100\Omega$ to some $k\Omega$
$C_d \approx 1$ to a few pF
$T_a = R_aC_d \approx 100$ps to few ns
$T_L = R_LC_d \approx 1$ to some µs

When the diode voltage goes down to $V_B$ the avalanche is no more self-sustaing. The avalanche is thus quenched by the action of $R_L$ and the circuit is called **Passive Quenching Circuit (PQC)**

# Passive Quenching Circuit with repeated triggering



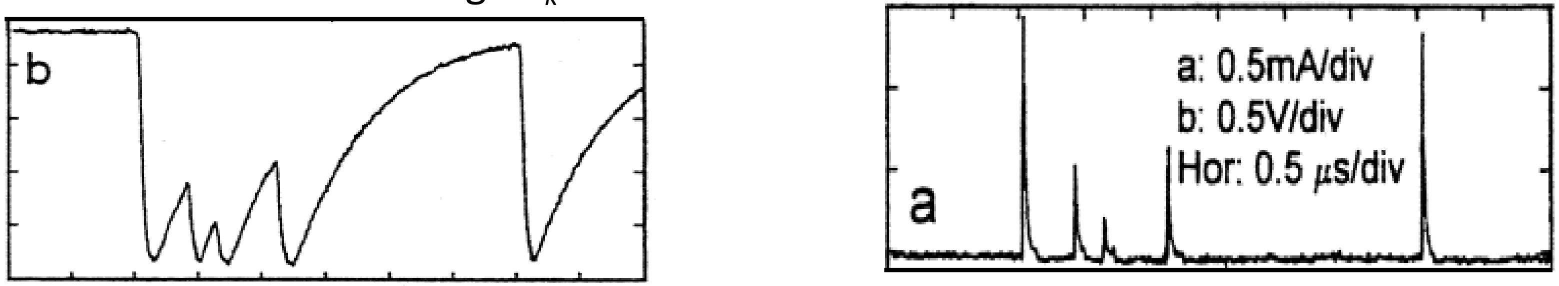
$R_a \approx 100\Omega$ to some $k\Omega$

$C_d \approx 1$ to a few pF

$R_aC_d \approx 100$ps to few ns

$R_LC_d \approx 1$ to some μs

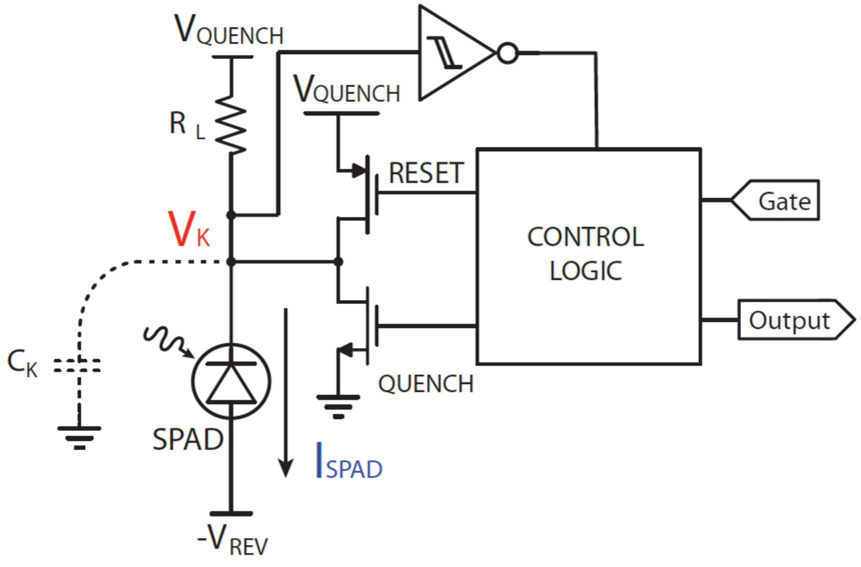
# Operation with Passive Quenching

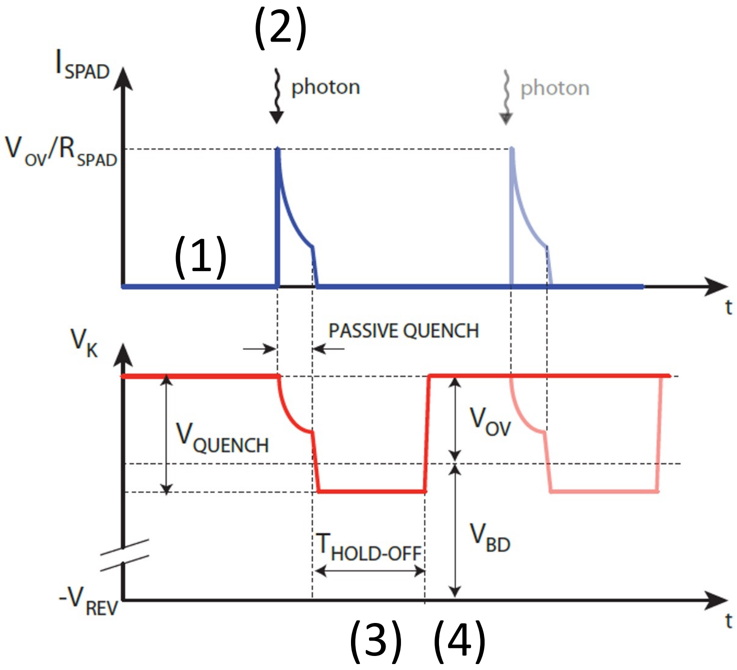

Diode Terminal Voltage $V_k$

Avalanche Current $I_a$

- In a passive-quenching circuit, after each quenching the diode voltage **slowly recovers from the breakdown voltage** $V_B$ to the supply level $V_S$.
- In photon counting with a PQC, **count losses are caused by the gradual recovery of the detection efficiency** from nil to the correct level after each quenching.
- In photon timing with an avalanche diode in PQC, for photons arriving during a voltage recovery the arrival time measured on the electrical output pulse suffers **increased delay and time-jitter with respect to the operation** at the correct diode voltage. This effect progressively degrades the time resolution as the pulse counting rate is increased
- In conclusion, the application to photon counting and timing of avalanche diodes in Geiger mode with a PQC has very limited interest. It is restricted to favorable cases, that is **cases with low dark-count rate, low count-rate of background photons and low count-rate of the signal photons**

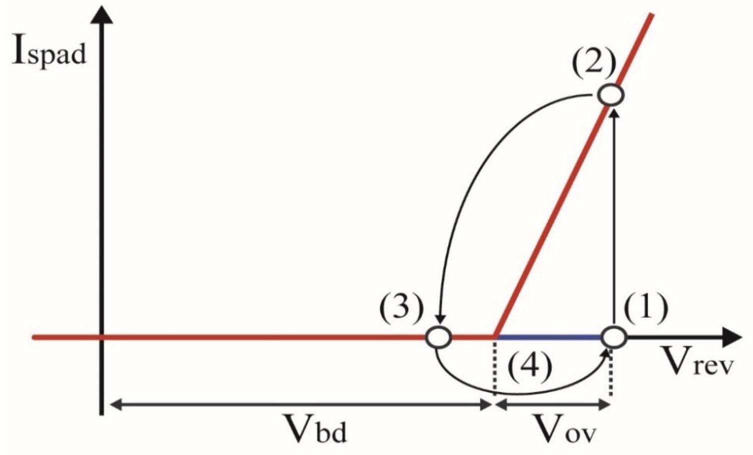
# Principle of Active Quenching Circuits (AQC)





**Active Quenching Circuit** drives the SPAD device providing:

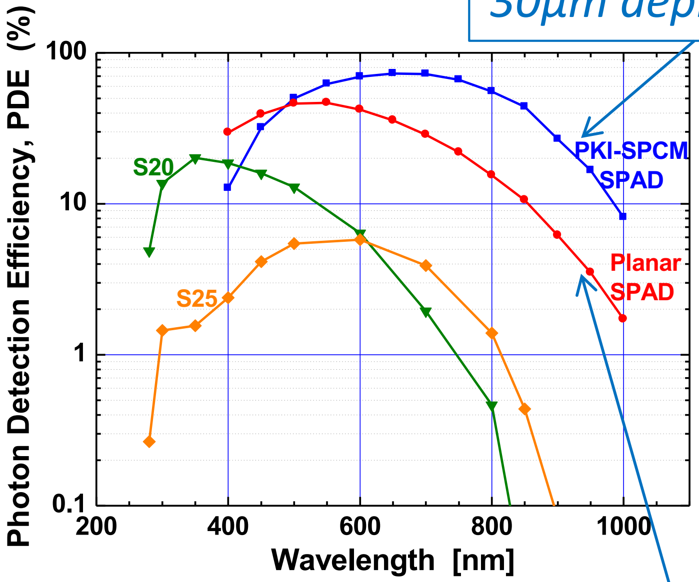
- short, well-defined deadtime
- high counting rate > 1 Mc/s
- good photon timing
- standard output



Overcoming the problems of the passive quenching circuit opens the way to high-speed SPAD applications

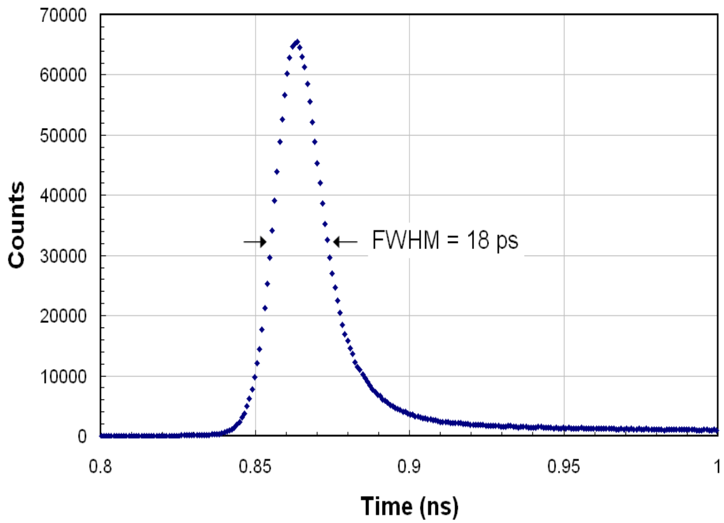
# Semiconductor SPADs vs. PMTs

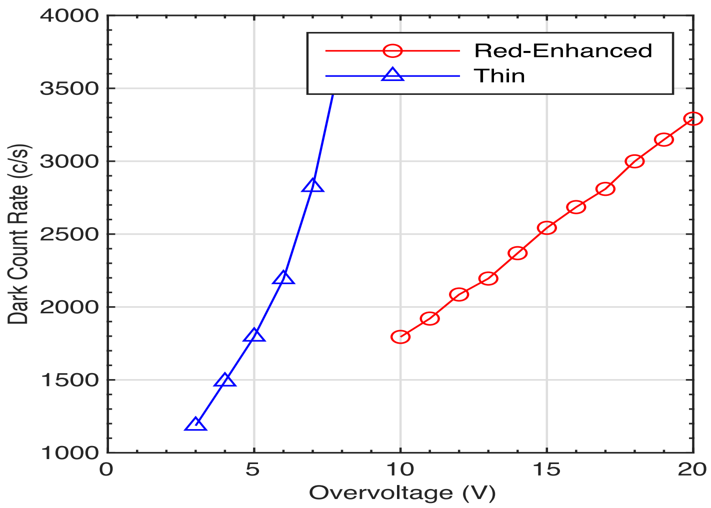
- **Microelectronic advantages:**
  Miniaturized, low voltage, etc..
  Insensitive to magnetic fields
- **Improved performance:**
  Higher Photon Detection Efficiency
  Comparable or lower noise (**but with much smaller area!**
  Better photon timing



*30µm depletion*

*1µm depletion*





# Challenges in SPAD development

**Microelectronic Technology**

**Strict control** of transition metal contamination

- ultra-clean fabrication process (defect concentration **$< 10^9$ cm$^{-3}$** )

**Device design**

**Electric field engineering**

avoids BB tunneling and reduces field-enhanced generation, with impact on:

→ dark count rate

→ dark count decrease with temperature

→ photon detection efficiency

→ photon timing jitter

**Front-end electronics**

**Low-level sensing of the avalanche current →** avoids or reduces trade-off between timing jitter and active area diameter

**Application-specific** electronics

# Time-Correlated Single Photon Counting (TCSPC)

**EXTRA COURSE**

# Why Single Photon Counting

- Direct digital detection
- Overcomes the limit of analog photodetectors, i.e. the circuit noise
- Noise only from the statistics of dark-counts and photons
- Measurement of light intensity with ultra-high sensitivity

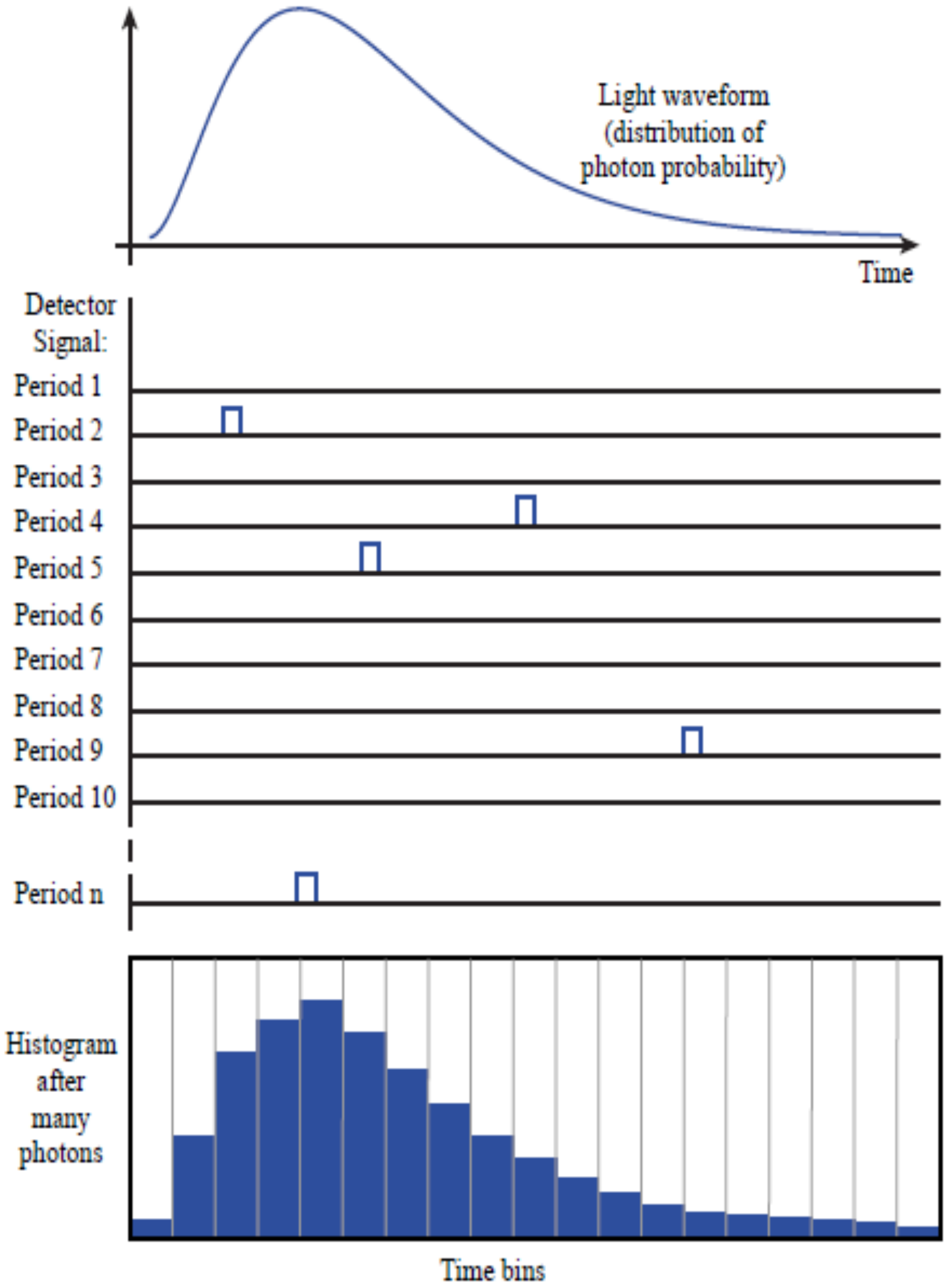
and with precise **photon-timing**

## Time-Correlated Single Photon Counting (TCSPC)

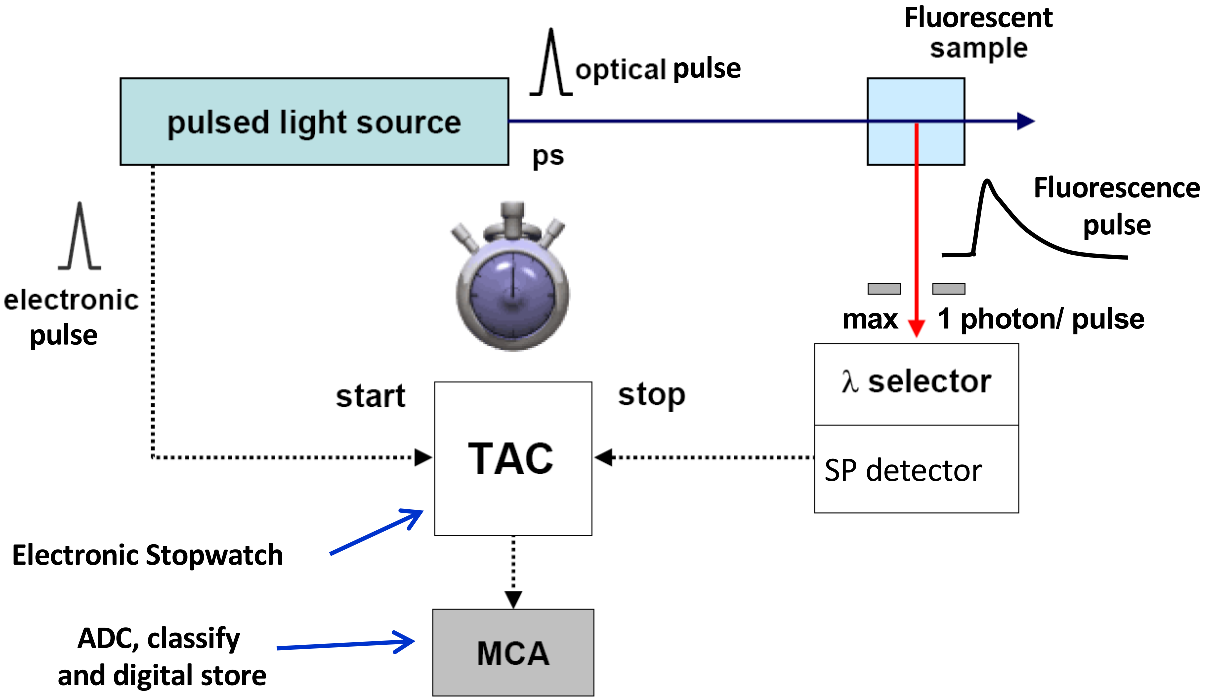
→ measurement of ultrafast waveforms with ultra-high sensitivity

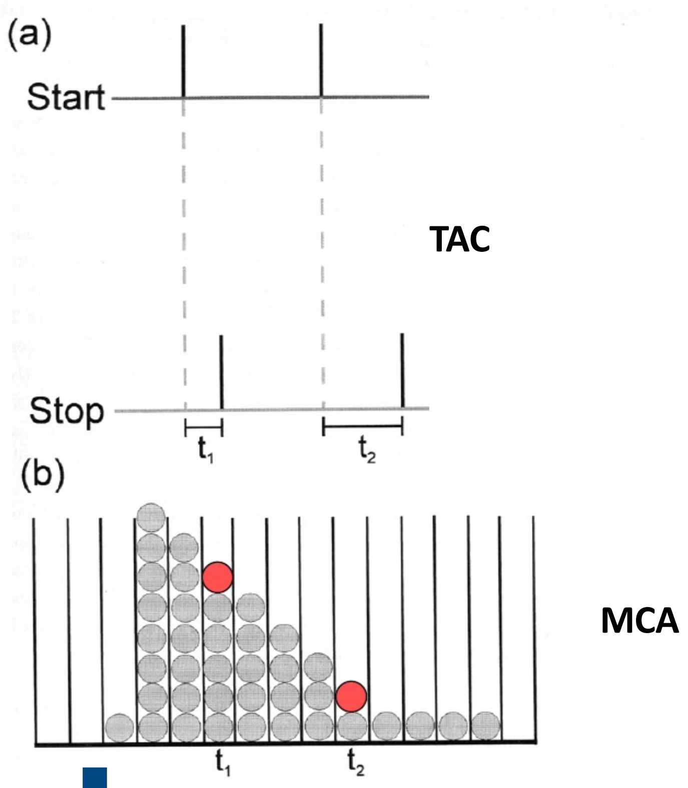
# TCSPC working principle

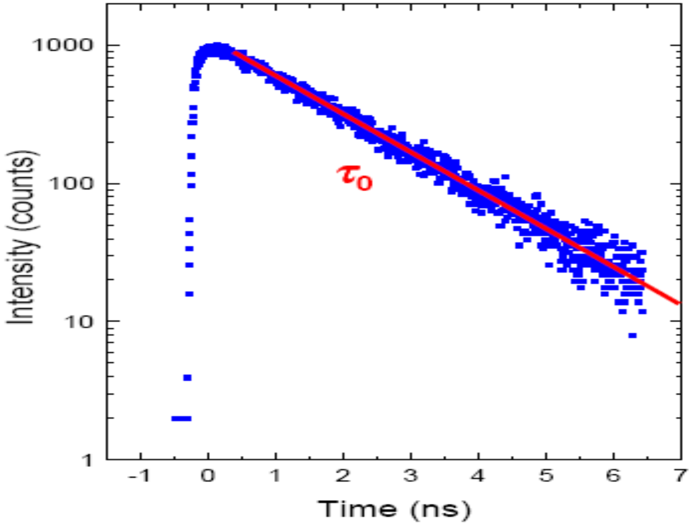
- Use a **periodical illumination** with a pulsed laser
- Measure the **time of arrival of each photon** re-emitted by the sample
- **Build a histogram** of the photons time of arrivals
- Upon the collection of a statistically significant amount of events, the **histogram corresponds to the waveform** you would have obtained with a single “analog” measurement.
- The equivalent bandwidth is not limited by the Single Electron Response (SER)



# Time Correlated Single Photon Counting (TCSPC)







**Hystogram of many trials**

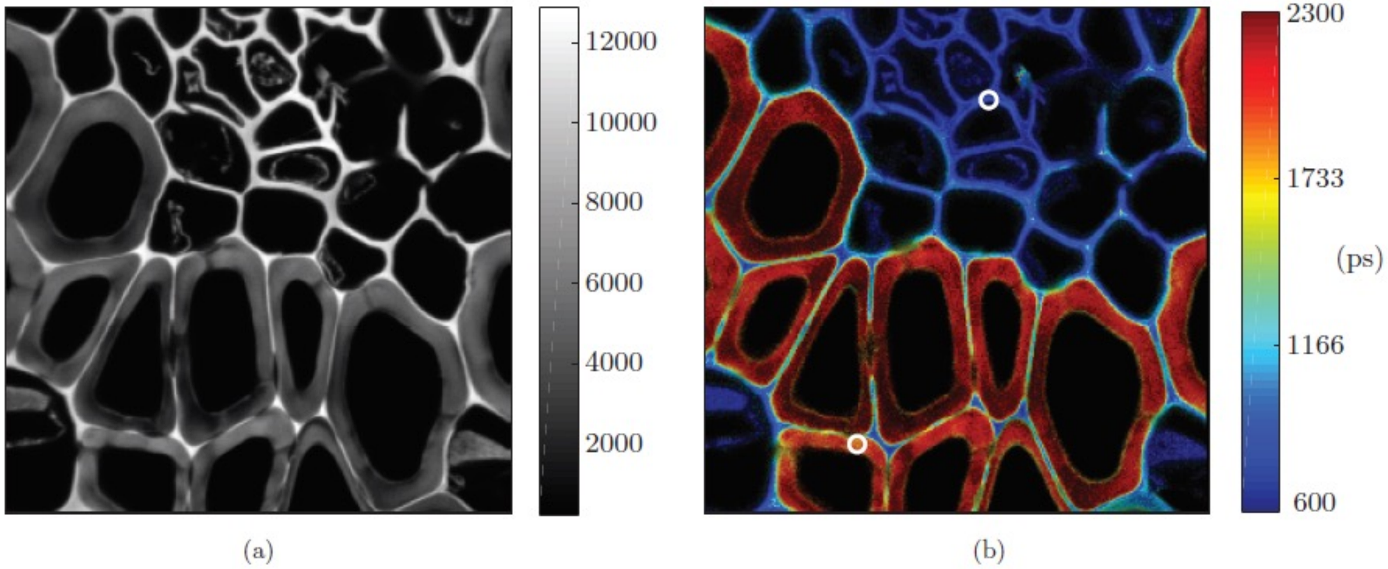
**≡**

**fluorescence decay curve**

# TCSPC - Applications

## Fluorescence Lifetime Imaging (FLIM)

- An excited molecule re-emits light with a peculiar time constant.
- Lifetime measurement is used to identify labeled molecules, proteins, cancer cells, toxic aggregates, etc.

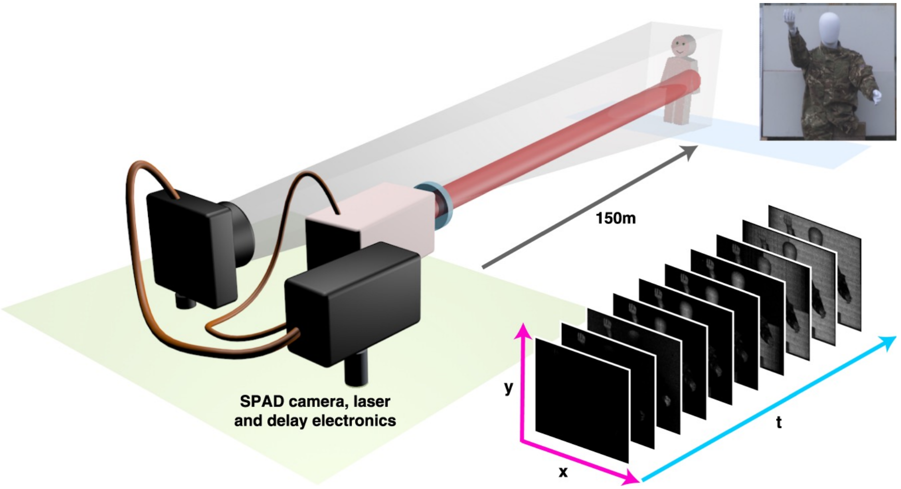


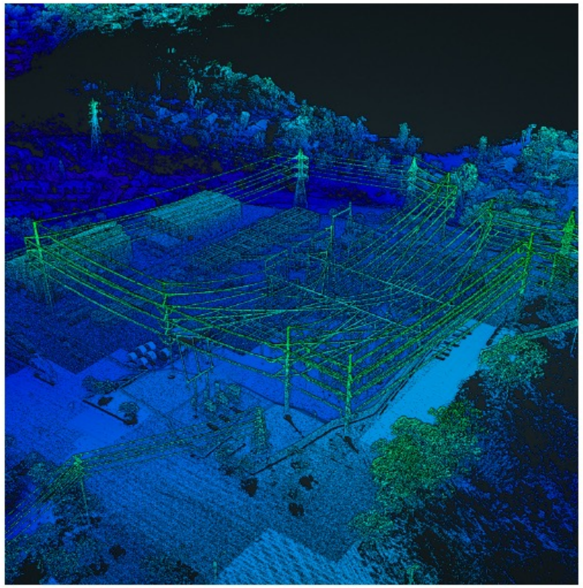
(a) Intensity image, (b) FLIM image. Two main lifetimes are visible in the FLIM image: one around 600ps and another one around 2.3ns

Collaboration between Politecnico di Milano and EURAC Research Centre

# TCSPC in Lidar applications

## Laser Imaging Detection and Ranging (LiDAR)





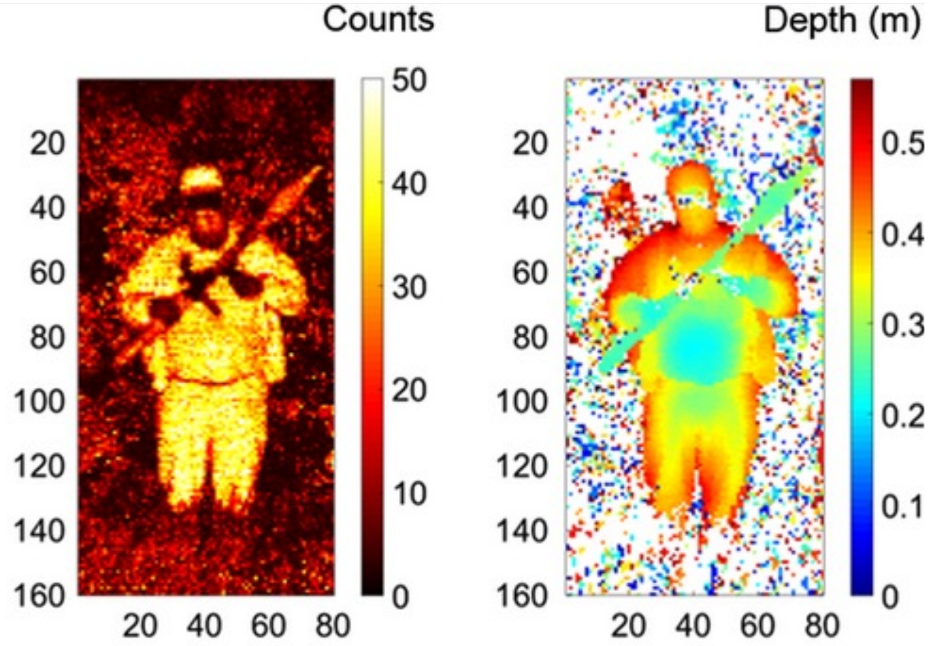
www.phoenixlidar.com

- Detailed map of utility infrastructure and power lines clearly visible from an altitude of 100 meters, traveling at 50 knots
- Very accurate info on distance is provided

# TCSPC in Lidar applications

Laser Imaging Detection and Ranging (LiDAR)

Courtesy of Dr. G. Buller, Heriot-Watt University



Imaging beyond barriers (nets, foliage, trees..)

# TCSPC – Current and future trend

## TCSPC speed has some intrinsic limitations

- In a TCSPC measurement, the laser power has to be tuned in order to ensure that the system works in single-photon regime
- Otherwise, detector dead time affects photon recording probability and it can lead to a distortion of the reconstructed curve because of pile-up
- In order to limit pile-up distortion, the average count rate of a single TCSPC acquisition chain is kept below 10% of the excitation rate (typically 1% or 5%)
- In this way, the probability of having two photons in a single excitation period is negligible and pile-up distortion is avoided
- Example: with a laser operating at 80MHz, the count rate is typically up to 4Mcps
- In order to have 10000counts, Tmeas=10000/4Mcps = 2.5ms for a single spot