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DEVICE PARAMETERS

PHOTON DETECTION EFFICIENCY

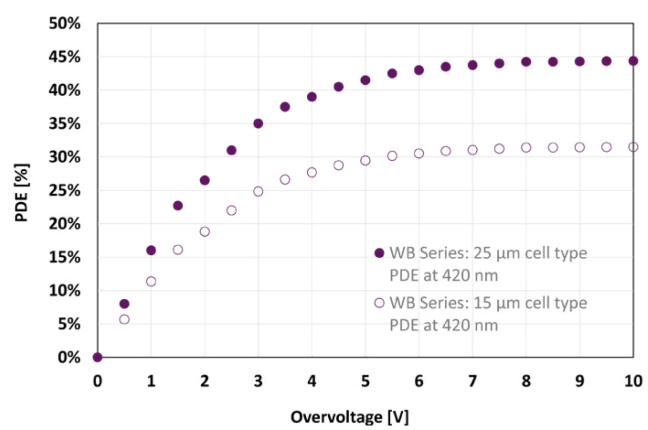
The photon detection efficiency (PDE) is defined as the number of photon-discharged microcells divided by the number of incident photons.

$$\mathrm{PDE}(\lambda, V) = \mathrm{QE}(\lambda) \cdot \varepsilon(V) \cdot \mathrm{GE}$$

QE = Quantum Efficiency | ε = Geiger Efficiency | GE = Geometrical Efficiency | λ = Wavelength | V = Bias Voltage

For SiPMs the PDE value depends on the applied overvoltage (cf. Figure 1) and the wavelength of the incoming photon (cf. Figure 2). First one is due to the fact that the Geiger efficiency is increasing with increasing overvoltage until it reaches its maximum. Second one is due to the very different interaction- and absorption behavior of light with different wavelengths in silicon. The KETEK SiPM has been optimized for blue light. This is amongst many other applications a perfect match for many scintillator materials like LSO, LYSO, NaI:Tl, CsI, GSO, Anthracen, etc.

Figure 1: Increase of PDE with rising overvoltage: The PDE is increasing with overvoltage until the Geiger efficiency gets maximal. The saturation regime starts at approximately 20% relative overvoltage. Example shows PM3315-WB and PM3325-WB measured at 420 nm.



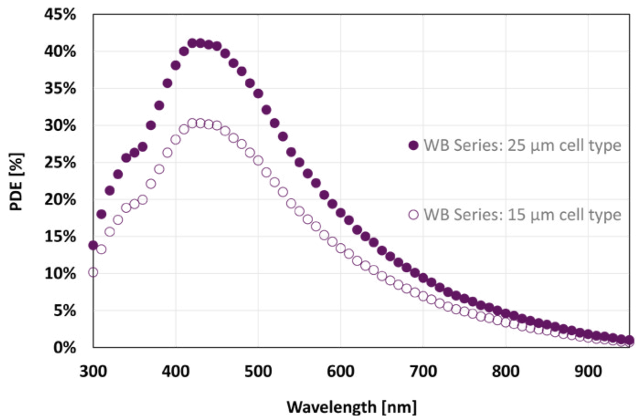


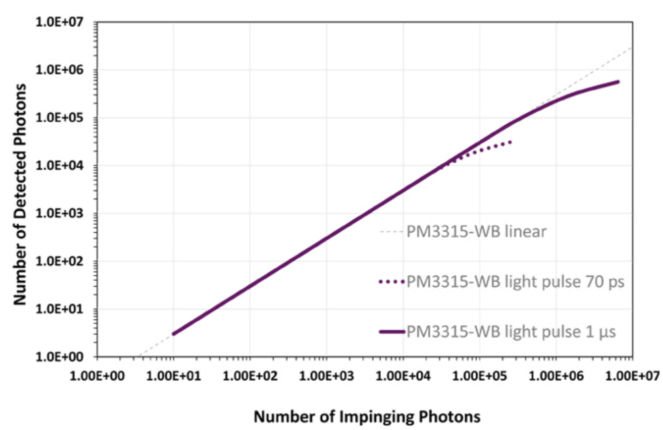
Figure 2: PDE vs. wavelength of the incoming photon with a peak sensitivity at 420 nm. All stated PDE values do not include noise effects like dark counts, crosstalk or afterpulsing and are based on Poisson statistics based measurements.
Example shows WB Series SiPMs at 5 V overvoltage.

LINEARITY

The photon detection efficiency (PDE) is defined as the number of photon-discharged microcells divided by the number of incident photons.

SiPMs show only in a limited range a linear response to the incident light. The two main parameters causing saturation are the limited number of available microcells and the recovery time of the microcells. The number of microcells is the only limit in case of very short light pulses (shorter than the recovery time) like the one shown in the example with 70 ps length. For longer light pulses like in the example for 1 µs length, it is also important that the cells recover as fast as possible again. Therefore in terms of linearity, PM3315-WB shows a linear behavior over a wider range compared to PM3325-WB, as it has both a higher number of cells (38800 vs. 13920) and also a shorter cell recovery time (13 ns vs. 40 ns). PM3325-WB instead has a higher microcell fill factor and therefore higher PDE than PM3315-WB.

Figure 1: Linearity of PM3315-WB measured at 4 V overvoltage and 420 nm.



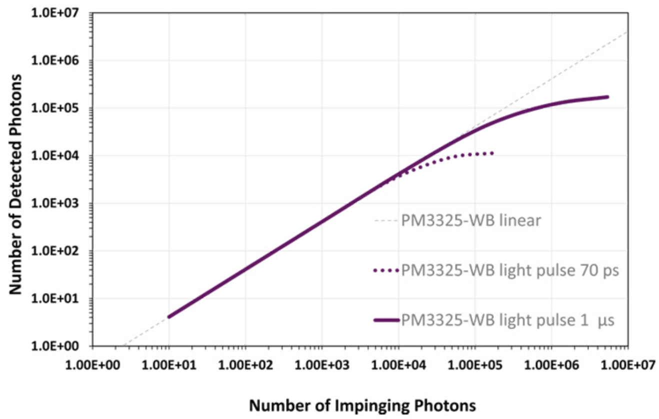


Figure 1: Linearity of PM3325-WB measured at 4 V overvoltage and 420 nm.

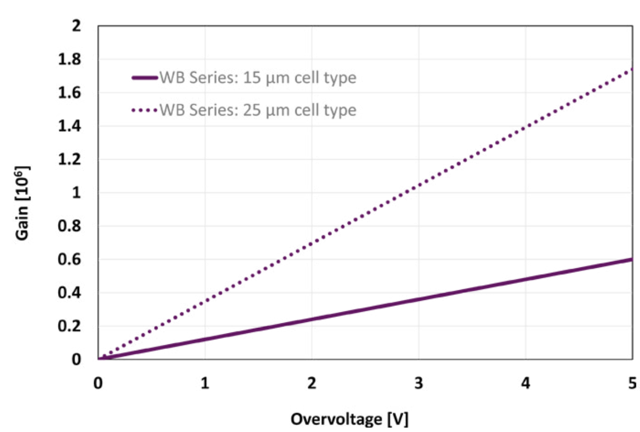
GAIN

The Geiger discharge of a micro pixel is proportional to the applied overvoltage $\Delta V = V_{Bias} - V_{Breakdown}$ and the microcell capacitance. When hit by a photon, each microcell produces a standardized signal regardless of its position on the SiPM. Due to almost no avalanche fluctuations the excess noise factor is very low and close to 1. Therefore the gain of a SiPM is scaling linearly with the applied overvoltage. Typically the gain of KETEK SiPMs is in the range of 10^5 to almost 10^7 (cf. Figure 3). Due to such a high gain typically single photons are already resulting in amplitudes of several mV at 50 Ω load.

$$\text{Gain} = \frac{C_{Pixel} \cdot \Delta V}{e} \propto \text{GE} \cdot \Delta V$$

C_{Pixel} = Capacitance of Microcell | ΔV = Overvoltage | GE = Geometrical Efficiency | e = Elementary Charge

Figure 3: KETEK SiPM gain for different microcell sizes. The gain is linear with overvoltage and is higher for larger cell sizes due to the increase in cell capacitance. Example shows PM3315-WB (15 µm cells) and PM3325-WB (25 µm cells).



TEMPERATURE COEFFICIENT

Avalanche diodes have a positive temperature coefficient of the breakdown voltage. This temperature coefficient is directly affecting the applied overvoltage and also the gain. The temperature coefficient of the gain is decreasing with increasing overvoltage. KETEK SiPMs show a very low temperature dependency which can make an adjustment of the bias voltage with temperature unnecessary and therefore can reduce system complexity and cost.

$$\frac{1}{G}\cdot\left(\frac{\partial G}{\partial T}\right)=-\frac{1}{\Delta V}\cdot\left(\frac{\partial V_{\mathrm{BD}}}{\partial T}\right)\approx\frac{-22\ \mathrm{mV}}{\Delta V}\cdot\mathrm{K}^{-1}$$

G = Gain | ΔV = Overvoltage | V_{BD} = Breakdown Voltage | T = Temperature

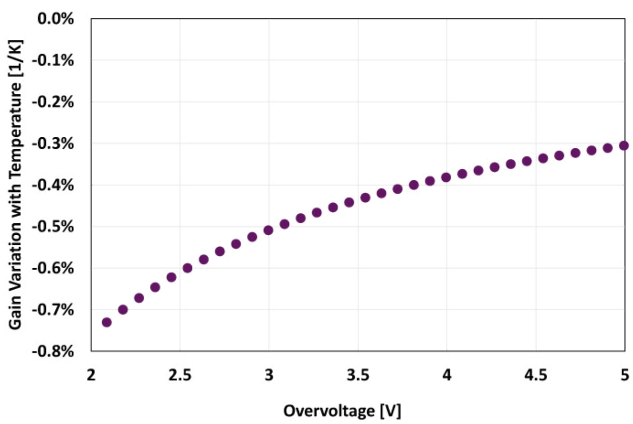


Figure 4: Temperature coefficient of the gain versus relative overvoltage. Valid for all KETEK SiPMs.

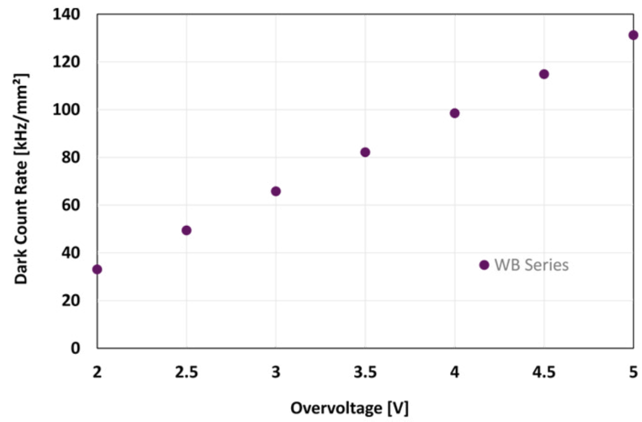
NOISE EFFECTS

Dark Count Rate

Pulses not being excited by incoming light are termed as dark pulses. They are triggered by thermally generated electrons and the frequency is termed as dark count rate. It is dependent on the overvoltage since higher overvoltage increases the breakdown probability (cf. Figure 5).

Secondly the dark count rate depends on the carrier density in silicon. Therefore it shows a strong dependency on the temperature. Roughly every 9°C the dark count rate is reduced by a factor of 2 (cf. Figure 6).

Figure 5: Dark count rate versus overvoltage WB Series SiPMs at 21°C.



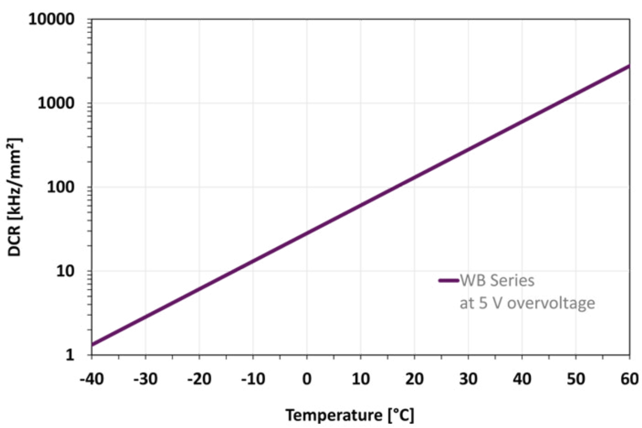


Figure 6: Dark count rate versus Temperature for the WB Series.

Optical Crosstalk

Depending on the number of electrons created during the Geiger discharge of a microcell about 3 to 50 secondary photons (in average three photons per 10^5 avalanche electrons) with a wavelength range from 450 nm to 1600 nm are emitted isotropically from the fired cell. These secondary photons are just like the incoming light able to cause a further Geiger discharge in case they are able to reach any other charged microcell within the SiPM (cf. Figure 7).

(1) Most obviously the secondary photons can travel directly to a neighboring cell (direct optical crosstalk),

(2) A secondary photon is able to generate an electron-hole-pair close to a neighboring cell. The carriers can diffuse to the microcell and cause their discharge (delayed optical crosstalk),

(3a, b) Secondary photons, being reflected at one of the various interfaces like e.g. package boundary or SiPM backside, can reach a neighboring cell via an indirect path (indirect optical cross talk).

The optical crosstalk mechanism according to (1) can be suppressed by a deep optical trench isolation between the individual microcells. In case the trench is deep enough, it helps also to suppress the crosstalk according to mechanism (2) by covering a larger solid angle.

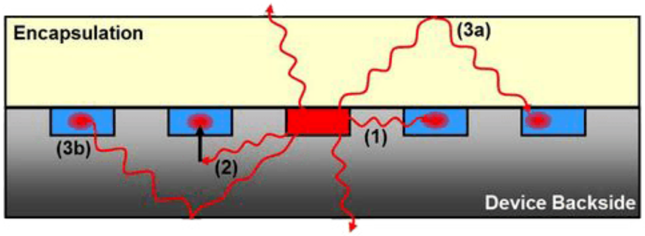
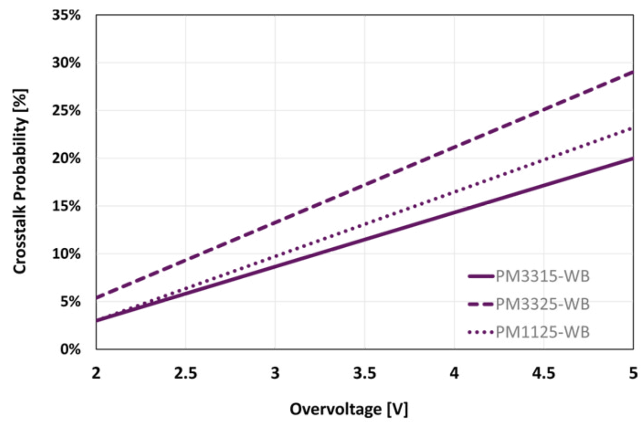


Figure 7: Schematic of optical cross talk mechanism.

Figure 8: Optical crosstalk probability versus overvoltage for WB Series SiPMs. It includes direct crosstalk which dominates and also delayed crosstalk (< 0.1%) which is almost negligible.



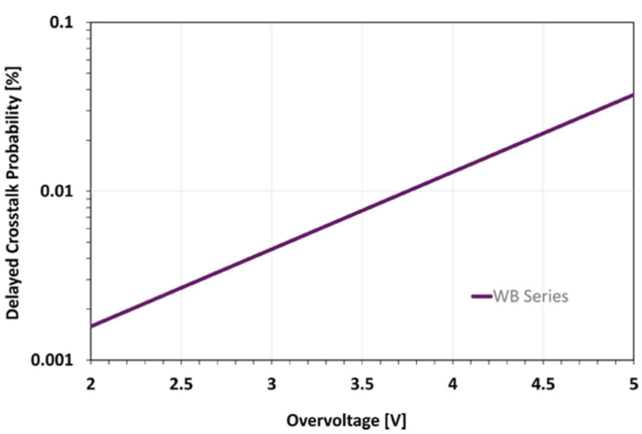
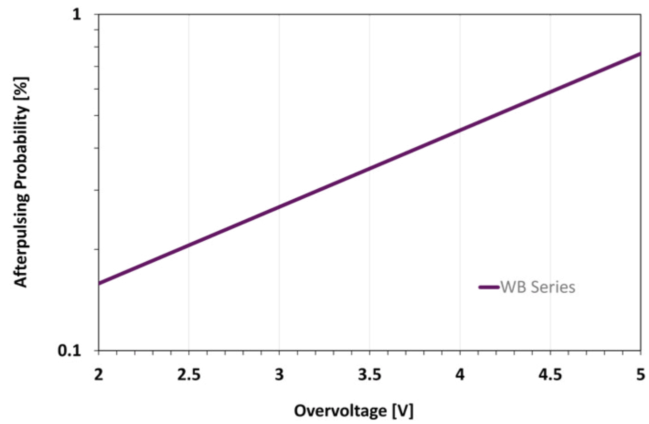


Figure 9: Delayed optical crosstalk probability of KETEK SiPMs. It is very low and negligible for most applications with a probability of < 0.1%.

Afterpulsing

During the breakdown and avalanche creation in a microcell, charge carries can get trapped
low afterpulsing of less than 1% (cf. Figure 10).

Figure 10: Afterpulsing probability of the WB Series SiPMs which show a very low value of < 1%.



Correlated Noise Probability

After a microcell has been fired, there is a certain probability for another breakdown after the inital one. Correlated noise includes afterpulsing and delayed crosstalk and is very low for KETEK SiPMs (cf. Figure 11).

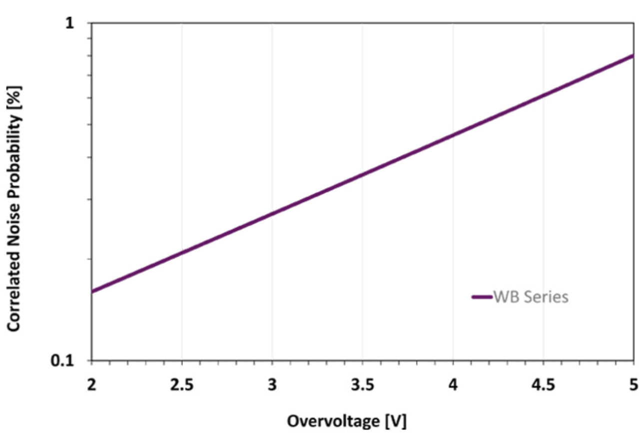


Figure 11: Correlated noise probability including afterpulsing and delayed crosstalk. Example shows the WB Series SiPMs.

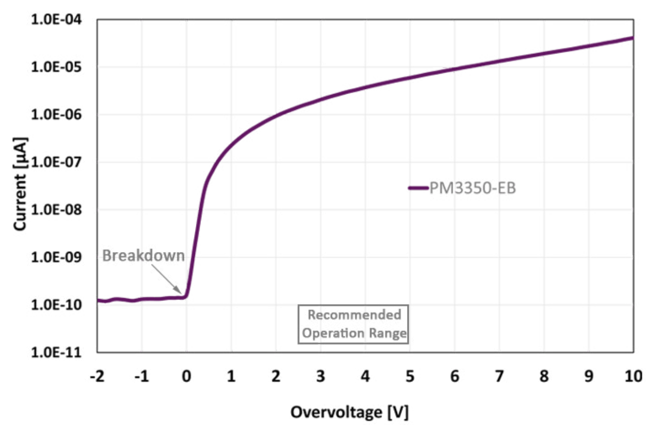
BREAKDOWN VOLTAGE

In contrast to APDs, SiPMs are operated above breakdown voltage. In this regime the current density is in the range of 10 µA/cm^2 up to 1 mA/cm^2. This dark current is caused by thermally generated electrons, which trigger the discharge of micropixels.

Below breakdown the current density is dominated by carrier diffusion and generation. The current level is typically 1 nA/cm^2 (cf. Figure 12).

SiPMs have a positive temperature coefficient of the breakdown voltage. The value of this temperature coefficient depends in a first approximation on the depth of the avalanche zone (cf. Figure 13 and section “GAIN”)

Figure 12: Current vs. overvoltage. Typical is the sudden rise at the breakdown voltage.
Example shows a PM3350-EB.



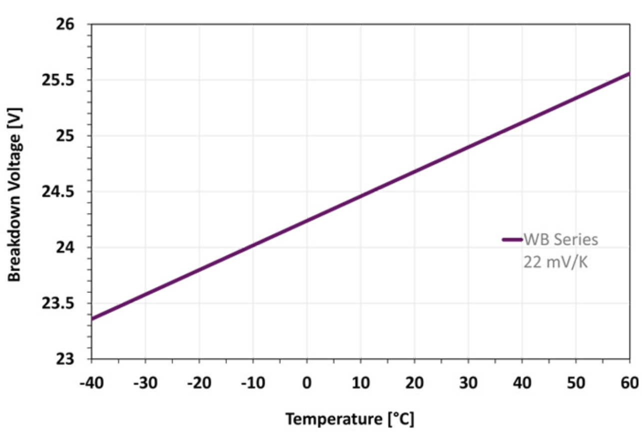
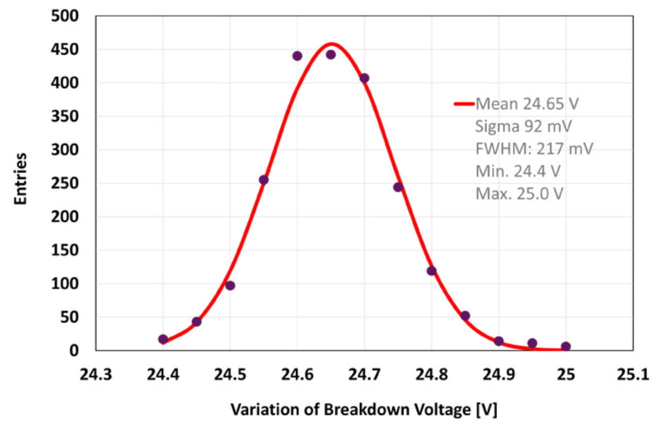


Figure 13: Breakdown Voltage versus Temperature for WB Series SiPMs.

Figure 14: Breakdown voltage variation of WB Series SiPMs. The distribution is very uniform with only a small spread. Minimal value is 24.3 V, maximum value is 25.0 V that is allowed to pass our qualification tests. Therefore it is possible to power many SiPMs together with the same bias line. This is important for the arrays, e.g. PA3325-WB-0808 and means, that also the gain is very uniform. This property of KETEK SiPMs allows a less complex system design and therefore reduced cost.



PULSE SHAPE

The pulse shape of KETEK SiPMs is asymmetric due to the fact that the dis- and recharging procedure of a fired SiPM microcell is determined by different RC values.
This behavior can be followed by an electrical model (cf. Figure 15) which has been proposed by F. Corsi et. al. in "Modeling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design." (DOI 10.1016/j.nima.2006.10.219)

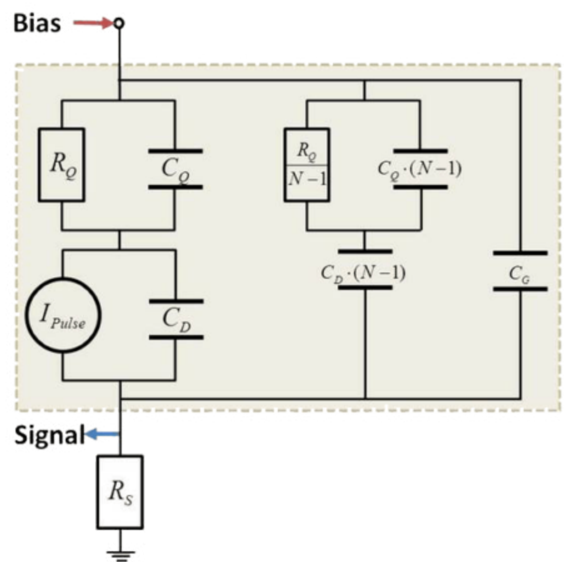


Figure 15: Electrical model of a SiPM as a signal source according to F. Corsi et. al.

The SiPM device is modeled here with the following single components:

C_D = Capacitance of the micro-Avalanche diode

I_{Pulse} = Internal current source representing the Geiger discharge

R_Q = Quenching resistor

C_Q = Parasitic quenching capacitance

C_G = Stray capacitance of all electrical traces

R_S = Series resistance

The time constant of the leading signal edge (rise time) is determined by the fired microcell capacitance and the series resistance according to

The signal tail has two different time constants:

A slow one which is determined by the quenching resistor and the micro cell capacitances according to

$$\tau_D = R_Q \cdot (C_D + C_Q)$$

A fast one which is determined by the series resistance, the parasitic quenching capacitance and the parasitic grid capacitance. It is only visible as long as the series resistance is small enough.

$$\tau_{\text{rise}} = R_S \cdot C_D$$

It is below 1 ns for KETEK SiPMs.

$$\tau_F = R_S \cdot (C_Q + C_G)$$

Figure 16 shows the pulse shape of PM3315-WB and PM3325-WB SiPMs measured with a 5 Ω series / load resistor as well as the exponential fits for the fast and the slow component. The signal rise time is clearly below 1 ns.

Figure 16: Pulse shape of KETEK PM3315-WB and PM3325-WB SiPMs.