New method for determination of non-quenching regime for silicon photomultipliers: A comparative study

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With increasing overbias voltage the most important parameter of silicon photomultipliers (SiPMs), the photon detection efficiency (PDE), increases and asymptotically reaches a saturated value which corresponds to the increase of Geiger efficiency. In turn, the dark count rate (initiated by thermally generated electron-hole pairs) is also increasing making it necessary to find a compromise.

New developments in SiPMs tend to minimize the dark count rate [1]. Therefore higher overbias voltages can be applied and the ability of the resistor to quench the avalanche becomes the limiting factor for reliable operation.

By determining the ratio of measured and calculated dark current, in which latter results from dark count rate, a disproportional increase identifies the initiation of the non-quenching regime.

First results of a comparative study demonstrate the capability of this new characterization method.

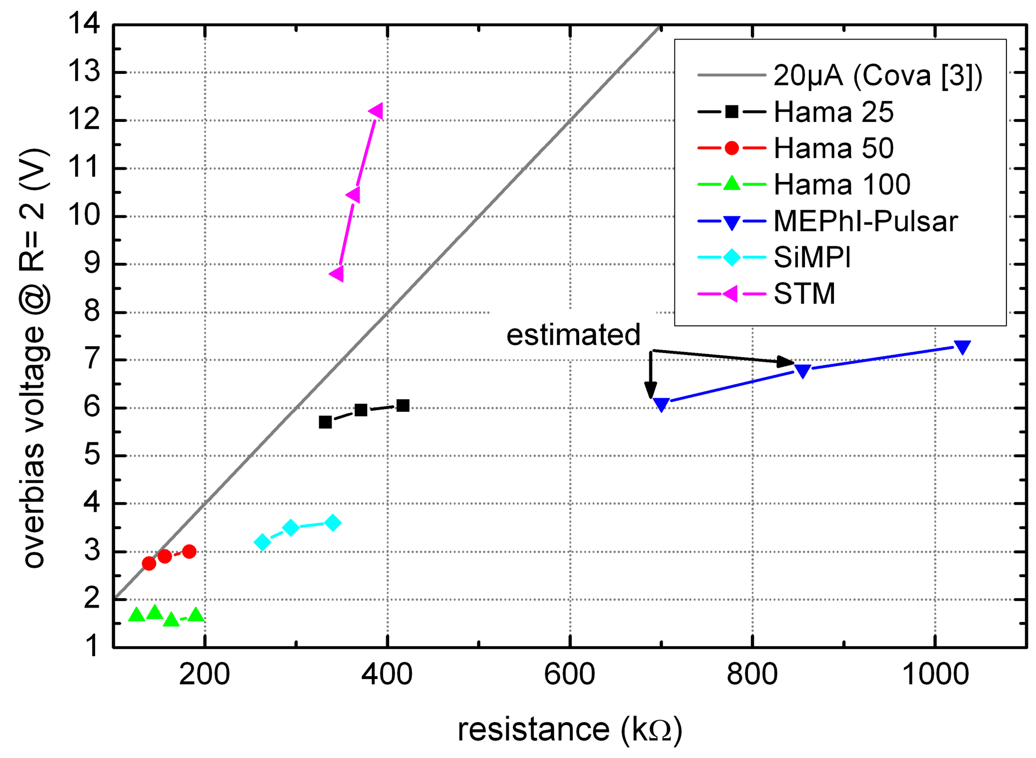

Fig 7: Overbias vs. resistance for a ratio of R = 2.

SiPM basics

An SiPM is an array of independent avalanche photo diodes (APD) which are operated in Geiger-mode (few volts above breakdown voltage). If a photon is absorbed in the sensitive area an electrical breakdown occurs. In order to be sensitive to successive photons every pixel has a quenching resistor in series to stop the avalanche process. The readout of all pixels is in parallel so the signal is the sum of all simultaneously fired cells. Fig. 1 shows an equivalent circuit of an SiPM cell.

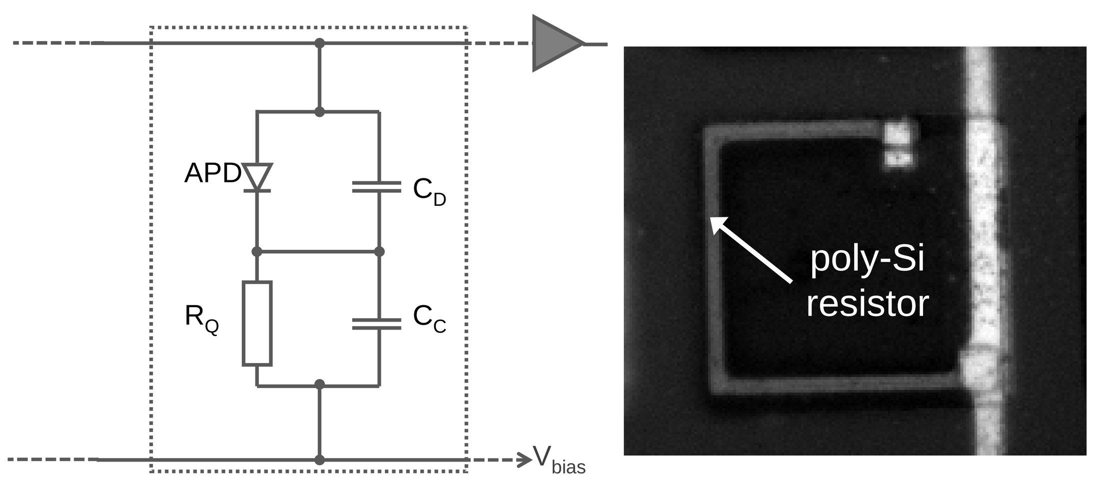

Fig. 1: Equivalent circuit for a silicon photomultiplier cell (left) and MEPhI device with polysilicon resistor (right).

Quenching resistor

The quenching resistors in this study are realized in two different ways:

Conventional quenching resistors consist of polysilicon and show negative temperature dependence *dR/dT*. They are deposited on the surface of the device, thus limiting the PDE by reducing the sensitive area of the sensor (see Fig. 1 right).

Fig. 2 shows the **Si**licon **M**ulti**P**ixel **l**ight detector (SiMPl) concept [2] in which the resistor is formed by the non-depleted regions of the silicon bulk. Compared to polysilicon the bulk material shows positive temperature dependence *dR/dT*.

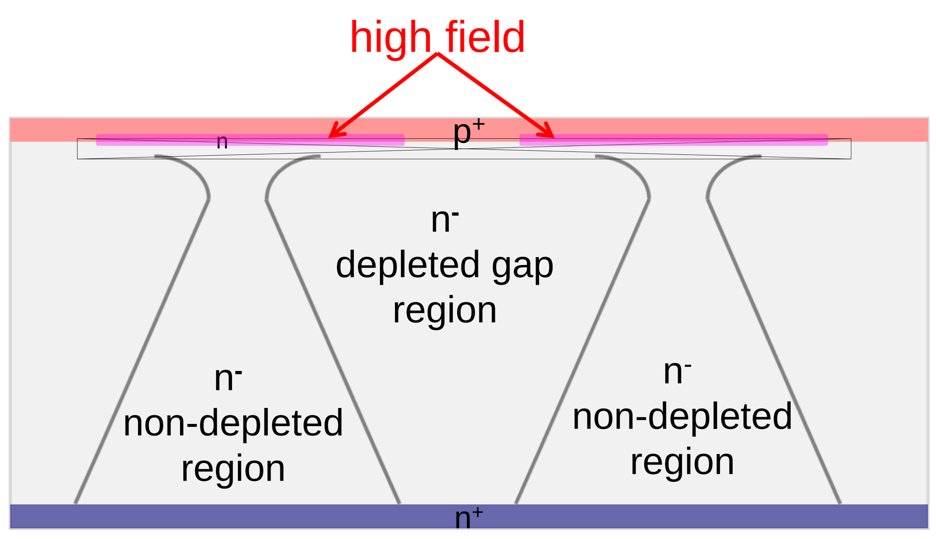

Fig. 2: Cross-section of a device with bulk-integrated quench resistor.

Device	Pitch (µm)	V_{break} (V)	R_{Cell} (kΩ)
Hamamatsu 25	25	69.4 (293K)	332
		68.4 (273K)	371
		67.5 (253K)	417
Hamamatsu 50	50	70.1 (293K)	139
		68.9 (273K)	156
		67.6 (253K)	183
Hamamatsu 100	100	70.2 (300K)	125
		68.7 (273K)	145
		67.6 (253K)	163
		66.5 (233K)	190
MEPhI-Pulsar	35	77.5 (293K)	700
		76.2 (273K)	855
		74.9 (253K)	1030
STMicroelectronics	60	28.7 (293K)	346
		28.3 (273K)	364
		27.8 (253K)	389
SiMPl	130 gap 11	35.2 (273K)	340
		34.5 (253K)	294
		33.9 (233K)	263

Table 1: Breakdown voltage and resistor value of compared devices.

Calculated current

In an ideal device the dark current through a diode is given by:

$$I = DC \cdot G \cdot e \qquad (1)$$

with *DC* dark count rate, *G* internal gain and elementary charge *e*.

For SiPMs the contribution of optical crosstalk (OCT) has to be taken into account since the dark count rate is only the number of the events above trigger level (here 0.5 photon equivalent).

By measuring the amplitude spectra an average number N_X of fired cells per trigger event can be calculated (see Fig. 3).

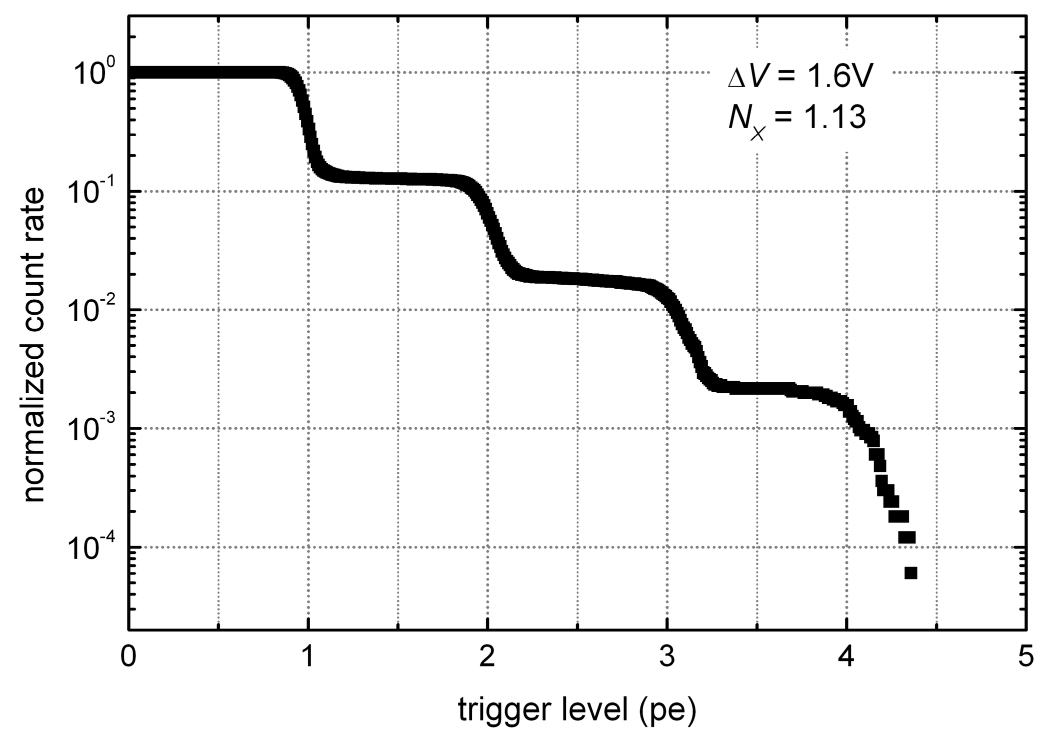

Fig. 3: Normalized dark count rate of Hamamatsu with 50 µm pitch calculated from amplitude spectra. The crosstalk contribution N_X *is determined by integration.*

Dark counts and gain were measured separately and a theoretical current was calculated using eq. 1 with *DC* replaced by $DC \cdot N_X$.

Measured current

The dark current through the device was measured with a Keithley 4200 with pA resolution (Fig. 4). The devices were stored in a light-tight climate chamber to obtain different values for the quenching resistor by changing the temperature.

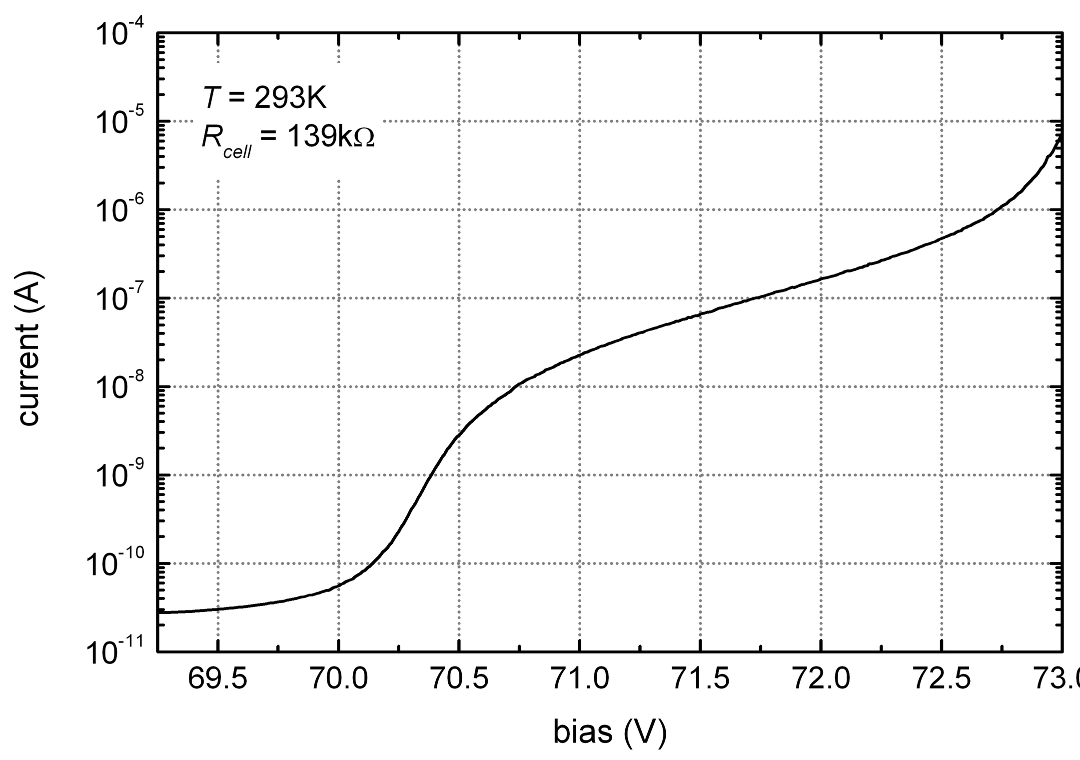

Fig. 4: IV-curve of Hamamatsu (50 µm pitch).

Polysilicon resistor

Figure 5 shows the current ratio vs. overbias for a Hamamatsu device with 50 µm pitch and polysilicon quench resistor. For small overbias the measured current can be fitted well by the calculated one (ratio = 1). The results are not corrected for afterpulsing what explains the small discrepancies at lower overbias. The initiation of the disproportional increase in current ratio is dependent on the resistance according to

$$I = \Delta V / R = const.$$

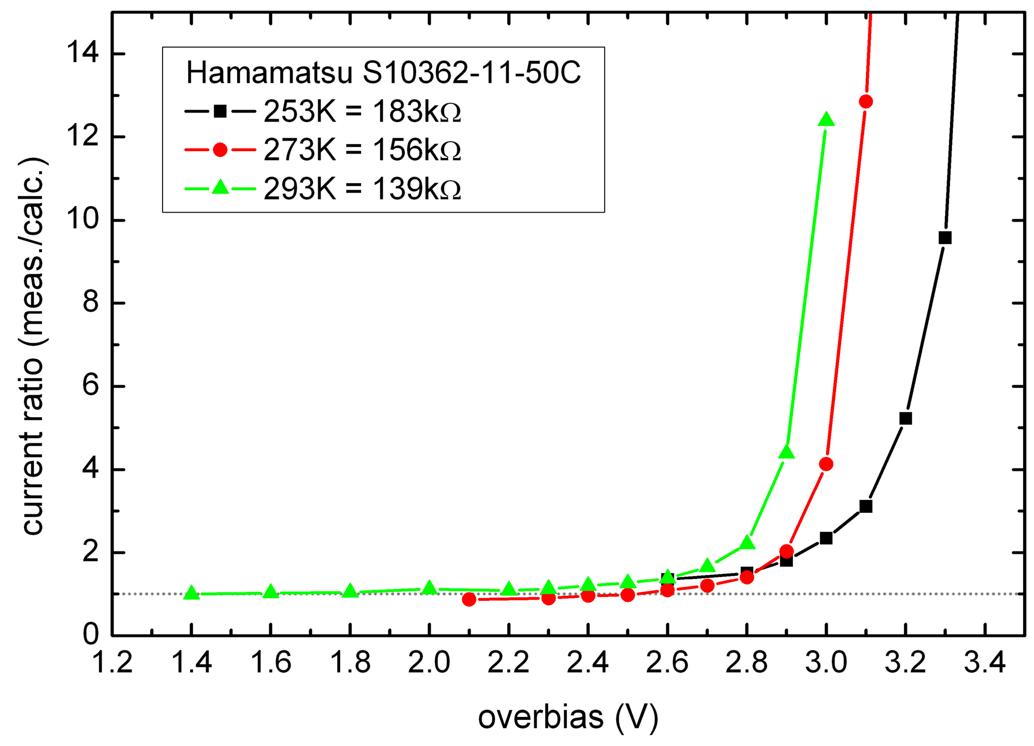

Fig. 5: Current ratio of Hamamatsu (50 µm). The dotted line displays a ratio of R = 1 which corresponds to a good agreement of measured and calculated value.

Bulk-integrated resistor

In Fig. 6 the current ratio for a device with bulk-integrated quenching resistor is shown. Compared to polysilicon resistors the silicon bulk material has positive temperature coefficient *dR/dT*, but the same dependency on resistance can be observed. Since the resistor values are larger for SiMPl the non-quenching starts at higher overbias.

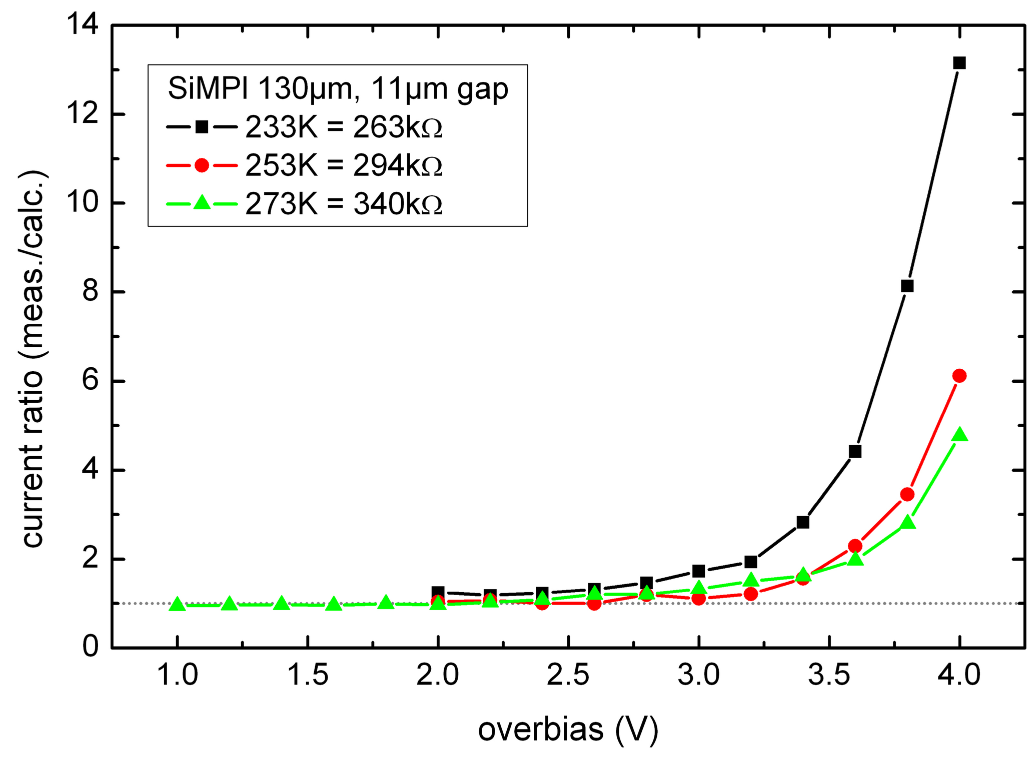

Fig. 6: Current ratio of SiMPl device with pitch of 130 µm and a gap of 11 µm. Temperature dependency is inverted, dependency on resistor value is the same.

Conclusion

First results demonstrate the capability of this new method to determine the non-quenching regime for SiPMs by comparing dark current and dark counts.

Tab. 1 shows the breakdown voltage and resistance of all devices in this study covering wide variations. In fig. 7 the overbias voltage at a ratio *R* = 2 is shown for all devices as a function of resistance. For comparison quench condition by Cova [3] is displayed, too. The disagreement illustrates that the new method allows a more precise definition of non-quenching condition for SiPMs compared to the 20µA rule of thumb. The results for the STM device are not yet fully understood. A strong inhomogeneity of the pixels was measured for this detector what could be an explanation for the behaviour.

Further devices will be studied and a correction for contribution of afterpulsing will be implemented in order to improve this new method.

References:

[1] McNally and Golovin, „Review of solid state photomultiplier developments by CPTA and photonique SA“, *NIM A*, vol. 610, no.1, 2009

[2] Ninkovic *et al.*, „SiMPl – an avalanche diode array with bulk integrated quench resistors for single photon detection“, *NIM A*, vol. 617, no. 1-3, 2010

[3] Cova *et al.*, „Avalanche photodiodes and quenching circuits for single-photon detection“, *Appl. Opt.*, vol. 35, no. 12, 1996

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