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Modelling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design

F. Corsi[a,*], A. Dragone[a], C. Marzocca[a], A. Del Guerra[b], P. Delizia[a], N. Dinu[c], C. Piemonte[c], M. Boscardin[c], G.F. Dalla Betta[d]

[a]DEE-Politecnico di Bari, Via Orabona 4, I-70125 Bari, Italy
[b]Department of Physics, University of Pisa, Largo Bruno Pontecorvo 3, I-56127 Pisa, Italy
[c]ITC-IRST, Via Sommarive 18, I-38050 Trento, Italy
[d]University of Trento, Via Mesiano 77, I-38050 Trento, Italy

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Abstract

Silicon photomultipliers (SiPM) have proven to be very attractive devices for low-energy photon detection. Thanks to their high gain and excellent timing resolution, they compare favourably to photomultiplier tubes (PMT) in many applications. Their electrical characteristics have to be taken into account to properly design the front-end electronics. Here, an electrical model of the SiPM is defined and an extraction procedure for the parameters involved in this model is proposed, based on suitable measurements performed on the real detector.

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Keywords: Photodetectors; Silicon photomultipliers; Parameter extraction

1. Introduction

Silicon photomultipliers (SiPM) have proven to be very attractive devices to detect low-energy photons, thanks to their high gain and excellent timing resolution. Moreover, they are not sensitive to magnetic fields and do not require high bias voltages [1,2], thus compare favourably to photomultiplier tubes (PMT) in many applications.

The definition of the most suitable front-end configuration for a SiPM detector requires a careful study of the static and dynamic characteristics of the device as a signal source. In particular, the total source capacitance and the shape of the current pulse produced in response to an incident photon are important parameters to be taken into account for a proper design of the front-end electronics and to assess correctly its performance when coupled to the detector. Here a suitable electrical model for the SiPM is proposed on the basis of the behaviour of each single microcell composing the whole detector structure. When hundreds of microcells are placed in parallel, the current pulse delivered to the external circuit by each single microcell in response to an event is affected by internal and external parasitics and load effects, which must be properly accounted for and modelled. An extraction procedure for the parameters included in the model, based on both static and dynamic measurements on the real device, has also been devised and the experimental results achieved by applying the technique to detectors realized with two different technologies will be shown.

2. Model and extraction procedure

The single microcell, which is replicated hundreds of times in the structure of a typical SiPM detector, is an avalanche photodiode operated in Geiger mode and passively quenched by means of an integrated resistor placed in series. The model of this elementary structure, which is biased a few volts above the breakdown voltage V_{br}, [3] includes the diode capacitance C_d, the quenching

*Corresponding author. Tel.: +39 080 5963265; fax: +39 080 5963410.
E-mail address: corsi@poliba.it (F. Corsi).

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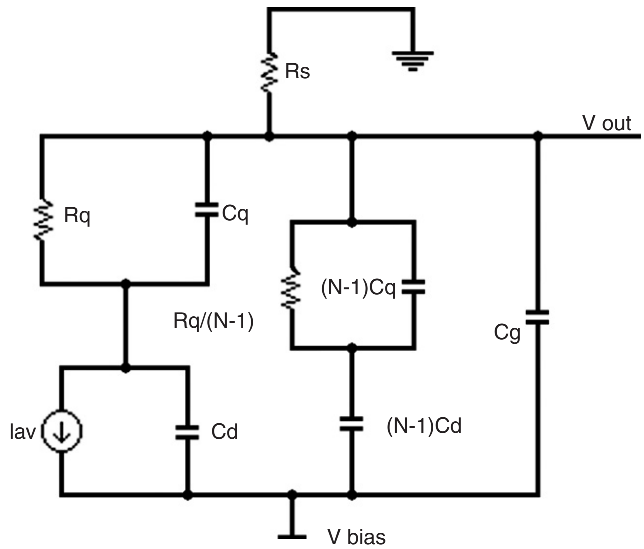

Fig. 1. Model of the whole SiPM.

Table 1
Model parameters extracted for two different devices

	SiPM IRST, $N = 625$, $V_{\mathrm{bias}} = 35\,\mathrm{V}$	SiPM Photonique, $N = 516$, $V_{\mathrm{bias}} = 63.8\,\mathrm{V}$
R_q (kΩ)	393.75	774
V_{br} (V)	31.2	61
Q (fC)	148.5	127.1
C_d (fF)	34.13	40.3
C_s (fF)	4.95	5.40
C_g (pF)	27.34	16.53

resistor R_q, a small parasitic capacitance C_q, placed in parallel to R_q, and a current source, which models the total charge delivered by the microcell during the Geiger discharge caused by an event. A further small capacitance C_p must be also considered in parallel to each microcell, to account for the parasitics between the substrate of the device and the contact of the quenching resistor. Fig. 1 shows the equivalent circuit of the SiPM resulting from a large number N of parallel-connected Geiger-mode (microcells) photodiodes. The figure highlights the case in which only one microcell at a time fires, as happens when a single dark current pulse is considered [4].

R_s represents the input resistance of the front-end electronics, usually very small (few tens of ohms), whereas C_g models the lumped contributions of the parasitics C_p. The value of the quenching resistors can be easily extracted from the characteristic of the SiPM in forward bias, in the region where the voltage on the diodes is almost constant and the ratio between the variations of voltage and current in the device is approximately equal to R_q/N. The value of the V_{br} can be also easily extracted with a curve tracer. A measurement of the impedance of the SiPM biased in the proximity of the breakdown voltage allows evaluating the equivalent parallel lumped values of the capacitance and conductance of the device, respectively, C_m and G_m. At the signal frequency used to perform this measurement (1 MHz), the overall contribution of the C_q capacitances is very small compared to R_q, and can be neglected. Using a suitable preamplifier of known gain, a typical dark current pulse can be read-out and exploited to evaluate the total charge Q delivered in the Geiger discharge of a single microcell, equal to $Q = (C_q + C_d)\Delta V$, where ΔV is the

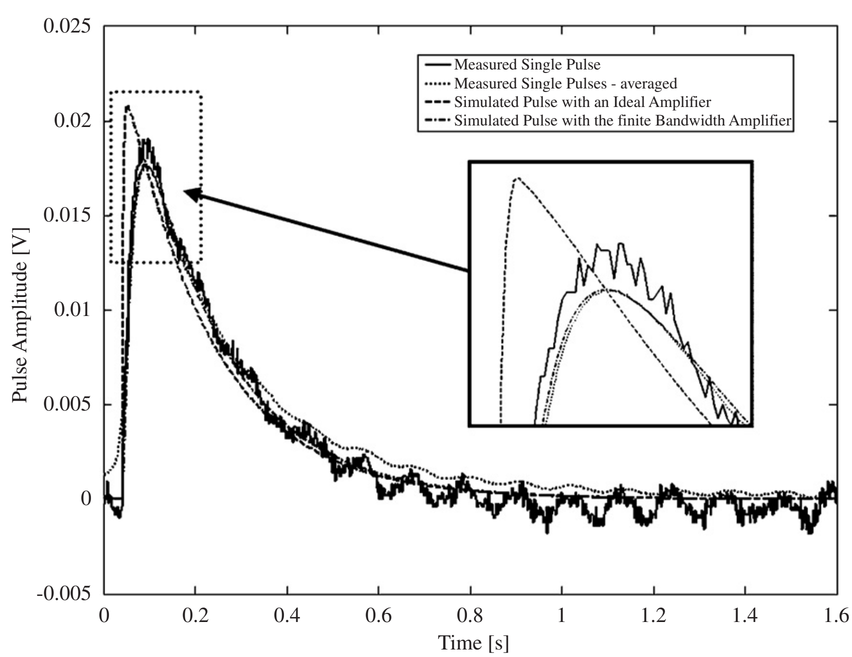

Fig. 2. Fitting of real data with the simulation results on the device model.

overvoltage $|V_{bias}|-V_{br}$. Thus the value of C_q+C_d is determined. Eventually four parameters, namely R_q, C_m, G_m and C_q+C_d, are available to extract the values of C_q, C_d and C_g of the model in Fig. 1. This task is accomplished according to the following equations:

(a)

$$C_{dTOT} = \sqrt{\frac{1+\omega^2 C_{TOT}^2 R_{qTOT}^2}{\omega^2 R_{qTOT}^2} G_m},$$

(b)

$$C_{qTOT} = C_{TOT} - C_{dTOT},$$

(c)

$$C_g = C_m - C_{dTOT} - \frac{\omega^2 C_{dTOT}^2 C_{TOT} R_{qTOT}^2}{1+\omega^2 C_{TOT}^2 R_{qTOT}^2},$$

where $\omega = 2\pi \times 10^6$, $C_{dTOT} = NC_d$, $C_{qTOT} = NC_q$, $C_{TOT} = C_{dTOT} + C_{qTOT} = NQ/\Delta V$ and $R_{qTOT} = R_q/N$.

Table 1 shows the results of the extraction procedure for two SiPM detectors from two different manufacturers.

Fig. 2 illustrates a fitting of the real data achieved by a circuit simulation performed using the parameters extracted from the measurements in the model of the SiPM.

Note that the simulation has been performed taking into account the finite bandwidth and the input resistance of the preamplifier used to observe the dark count pulses.

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