Modeling of New High Density NUV Sensitive Silicon Photomultiplier

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In recent years, Silicon Photomultipliers (SiPMs) have proven to be very performing devices, especially for those applications where high sensitivity to low intensity light and fast responses are required. A SiPM consists of a system of hundreds of p-n junctions connected in parallel and operating in Geiger mode. We performed a very detailed modeling of the Near Ultraviolet High Density (NUV-HD) devices produced by Fondazione Bruno Kessler (FBK), focusing on the cell capacitance, quenching resistance and parasitic capacitances. We measured the I-V and C-V responses and carefully studied waveforms acquired from sensors conditioned by a simple trans-impedance amplifier, thus obtaining information on the microscopic characteristic of the device. Results regarding the modeling as a function of the overvoltage will be presented and compared with simulations.

Introduction

The schematic representation of a SiPM is given and studied in several papers [1,2]. As shown in Fig.1, it mainly consists of a number of p-n junctions connected in parallel, in reverse bias regime and operating in Geiger mode. Each cell is represented by a detector capacitance C_d, an external quenching resistor R_q and a parasitic capacitance of the quenching resistor C_q. An additional parallel bulk capacitance C_g is added in parallel to the cells. R_L represents the input resistance of the preamplifier. We assumed the model described in [1] and tested this model against the new NUV-HD SiPMs produced by FBK with cell pitch of 40, 30 and 25 µm and 1mm x 1mm total area [3]. All measurements were performed using the trans-impedance AdvanSiD preamplifier [4].

Modeling

Following the method described in [1], we measured the direct and reverse I-V characteristics, obtaining the values of the quenching resistor R_q and the break-down voltage V_{br}. We found for the three devices a value of R_q = (1670 ± 0.01) kΩ and V_{br} = 27.7 V. The C-V characteristic was measured using a LRC meter Agilent 4284A, varying the reverse bias voltage from 0 V to 40 V. This measurement does provide useful indications on the internal cell and parasitic capacitances only below V_{br}, when the measurement is not contaminated by the spurious dark signals of the device. However, the observed trend of the capacitance and conductance of the devices did not show any saturation effect below V_{br}, suggesting that the p-n junction was not completely depleted at this voltage. This feature is typical of these devices and has been already pointed out in [3].

As a consequence, we derived the values of the internal capacitances of the devices directly fitting the experimental waveform with the one predicted by this model.

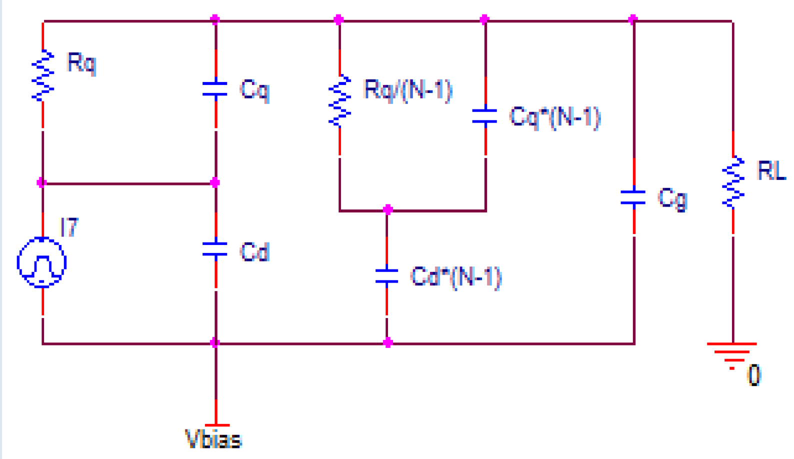

Fig.1: Schematic representation of a SiPM.

Fitting procedure

The optimization of the internal parameters of the SiPM was performed with a simple χ^2 fit in the Fourier space. From the model described in [1] we derived the expression of the transfer function of the SiPM, i.e. the current response of the circuit to a Dirac δ current pulse, assuming a R_L of 20 Ω:

$$H_{SiPM} = \frac{1+s\,\tau_q}{(1+s\,\tau_1)(1+s\,\tau_2)}$$

where $\tau_q = R_q C_q$, while τ_1 and τ_2 can be easily approximated with the following expressions, if typical values of the internal parameters for these devices are assumed:

$$\tau_1 \approx R_q(C_d + C_q),\ \tau_2 \approx C_d C_g R_L/(C_d + C_q)$$

The time constant τ_1, which is the slowest one of the circuit, represents the recharge time of the SiPM and is responsible of the long tail observed in the output signal.

It must be noted that our experimental measurements are not sensitive to the time constant τ_2 (and as a consequence to the value of C_g), since the bandwidth of the preamplifier is too narrow to allow its observation. We measured the transfer function of the preamplifier H_{ampl} and included it in the model to take into account this effect.

The final expression of the output signal in the Fourier space is:

$$V_{out} = H_{SiPM} H_{ampl} I_{in}$$

where I_{in} is the Fourier transform of a short current pulse of the duration of 10 ps. This approximation (Dirac δ assumption) is consistent, being the avalanche formation and self-quenching process much faster than the time constants of the circuit.

The V_{out} expression was fitted to the Fourier transform of the experimental waveform, which was obtained from an offline analysis of the SiPM signals acquired using an oscilloscope (see Simone's poster for more details).

The fit was performed independently for each device and for many values of reverse bias voltage, in order to study the dependence of the internal capacitances with the V_{bias}.

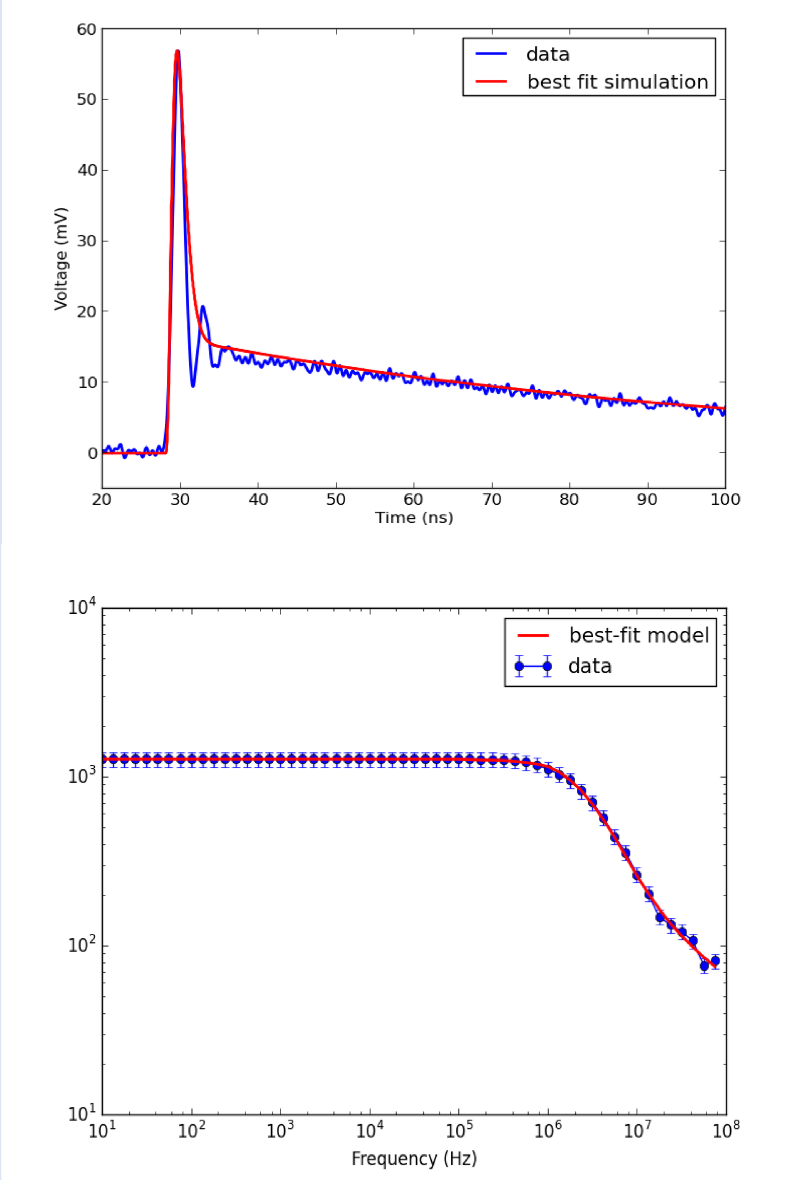

Fig.2: Experimental and best fit waveforms (top) and their Fourier transform (bottom) of the 30 µm cell pitch device at V_{bias}= 37 V .

Fit results

Fig. 2 shows the comparison of the experimental and theoretical waveforms, in the Fourier and time domain. As an example, the waveforms of the 30 µm cell pitch device at V_{bias} = 37 V are shown.

Fig. 3 and 4 show the best-fit values of C_d and C_q obtained for the three devices as a function of the over-voltage OV = V_{bias}-V_{br}. Typical values are tens of fF for C_d and few fF for C_q.

C_q does not show any dependence with over-voltage, while C_d decreases with the increase of the V_{bias}, especially for the 40 µm and 30 µm cell pitch devices, confirming that the depletion layer has not reached the junction width yet.

In the case of 25 µm cell pitch SiPM, a saturation effect is visible around the value of OV = 6 V, suggesting that at this voltage the p-n junction is fully depleted.

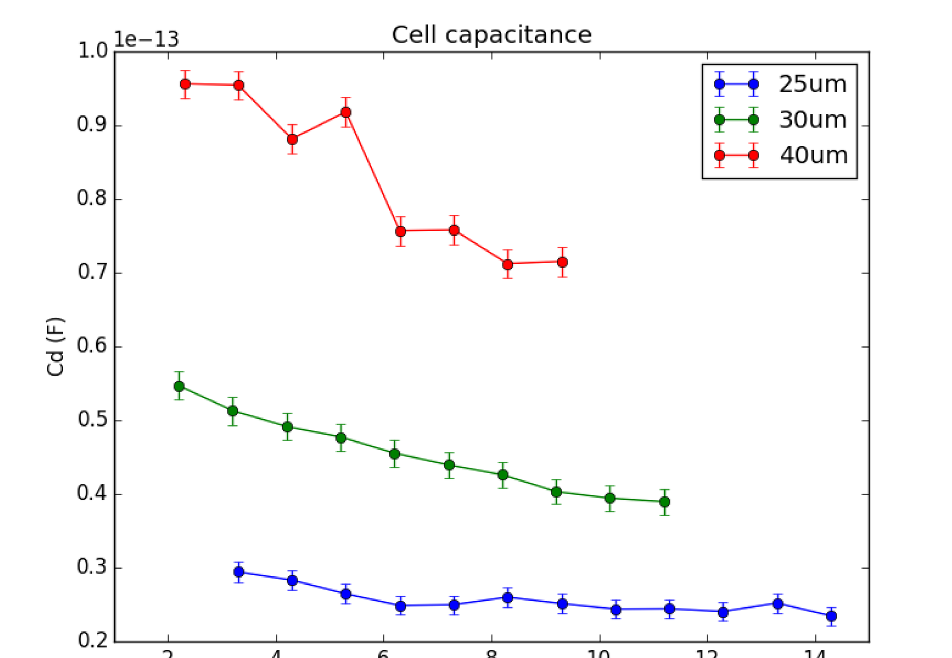

Fig.3: Best-fit values of C_d obtained for the three devices as a function of the over-voltage OV = V_{bias}-V_{br}.

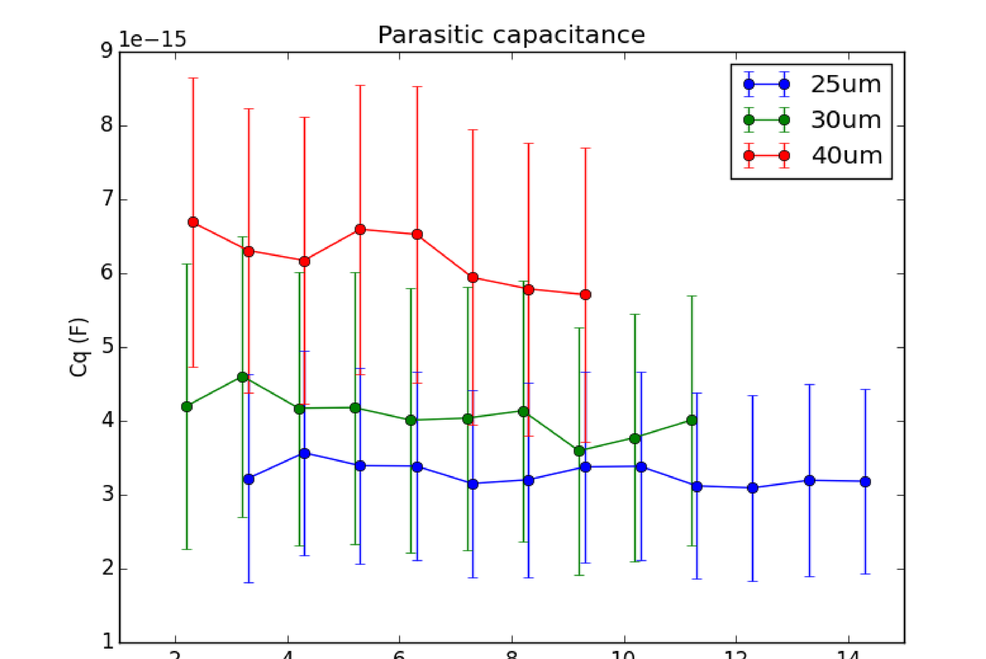

Fig.4: Best-fit values of C_q and for the three devices as a function of the over-voltage OV = V_{bias}-V_{br}.

Conclusions and remarks

The fitting procedure that we described allowed an easy derivation of the internal parameters of the SiPM directly from the experimental waveform. The only experimental measurement adopted so far is the value of the R_q, since for these devices any capacitance measurement in the static regime (i.e. below the breakdown voltage) is not valid in the dynamic one any more. However, following the procedure in [1], the avalanche charge produced by a single photo-electron signal can be correlated with the sum of C_d and C_q through the relation: Q = (C_d+C_q)*OV = C_{tot} * OV. An experimental measurement of Q is provided by the waveform analysis.

Figure 5 represents a comparison of the values of C_{tot} obtained from the fit and the ones obtained from the experimental measurement of Q for the three devices. The plot highlights a disagreement between these values, with the experimental value of C_{tot} systematically greater than the fitted one. In conclusion a deeper investigation of the SiPM model is necessary to fully describe these devices.

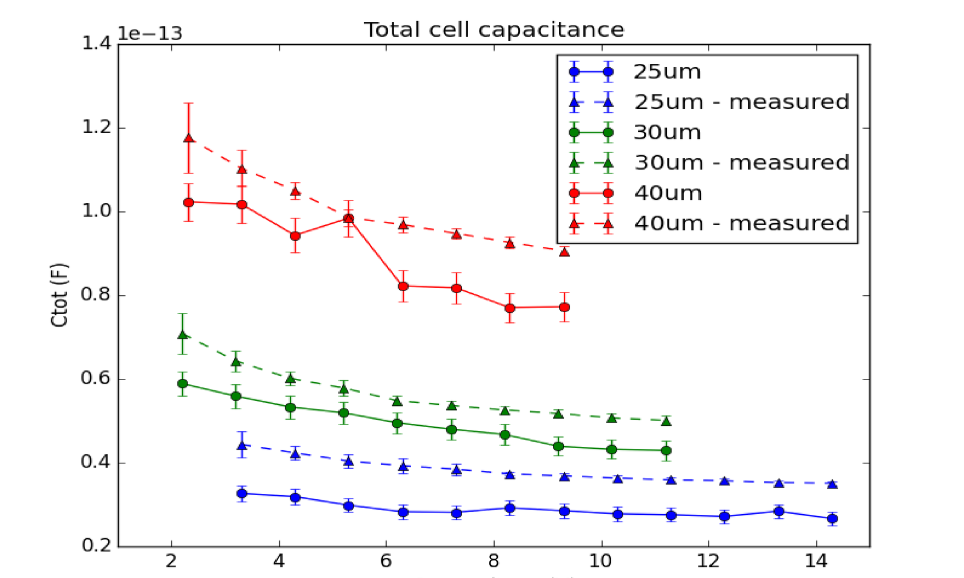

Fig.5: Comparison of experimental and fitted values of C_{tot} .

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