Characterization Measurements Methodology and Instrumental Set-Up Optimization for New SiPM Detectors—Part I: Electrical Tests

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***Abstract*— A comprehensive and in-depth characterization procedure for obtaining very accurate measurements on silicon photomultiplier (SiPM) detectors is described here. A large amount of electro-optical tests are systematically carried out in terms of the most significant SiPM performance parameters; in particular, an accurate estimation of the photon detection efficiency is achieved, based on the single-photon counting technique, with substraction of the dark noise contribution and avoiding the additional noise sources of crosstalk and after pulsing. Some recently produced detectors are analyzed and their relevant electro-optical parameters are evaluated in order to confirm the effectiveness and efficacy of the adopted characterization procedure in assessing the overall SiPM performance. The repeatability of measurements is carefully verified. All evaluated parameter trends are proved to be compatible with the physics theory of the SiPM device.**

***Index Terms*— Electro-optical characterizations, precision measurements, silicon photomultipliers, solid-state detectors.**

I. Introduction

To KEEP pace with the contemporary evolution of medical imaging, nuclear science and astroparticle physics, the realization of optical semiconductor detectors has been arousing a continuously increasing interest and is gaining a widespread popularity and diffusion within the scientific community.

Silicon Photo-Multiplier detectors (SiPMs), also referred to as Multi-Pixel Photon Counters (MPPCs), have been given considerable research attention over recent years. The outstanding characteristics offered by most commercially available devices in terms of high photon detection effeciency, excellent timing resolution, fast transient response, along with intrinsic ruggedness, robustness and low-power consumption, result from modern integration concepts and fabrication technologies.

In line with the rapidly growing number of perspective applications exploiting the benefits of the SiPM devices, remarkable research studies and technological development in this class of detectors have been worldwide undertaken by a rising number of companies and institutions [1]–[19].

SiPM detectors promise to fulfill a wide set of requirements coming from a large number of emerging contexts, and several silicon foundries primarily driven by the physical and medical fields are currently investing in future development and innovation. Recently, new SiPM detectors with enhanced overall features have been produced by the world leading manufacturers, and further performance improvements are shortly foreseen.

To understand the real applicability of SiPM detectors in the selected field, a very accurate experimental set-up and a well-defined methodology for measuring the electro-optical characteristics are required, with the primary aim to explain how accurate measurements and systematic data-handling procedures for the evaluation of the relevant electro-optical parameters can be profitably exploited to qualify the detector performance.

The systematic procedures followed to derive the main SiPM performace parameters, along with the extensive analyses and measurements performed on different devices, permitted a standardization of the adopted testing methodology, in order to be applicable to every kind of solid-state detectors produced by all manufacturing industries.

SiPMs basically consist of a parallel array of photon counting microcells, including a single-photon avalanche diode (SPAD) and a quenching element, delivering an output signal directly proportional to the incident photon flux [16], [17].

The present part of the paper is devoted to the electrical characterization of the SiPM detectors, in terms of breakdown voltage assessment, intrinsic gain evaluation, model parameters extraction and temperature dependence estimation. Since electrical measurement results give indications on the real operating conditions of the SiPM devices under test, they are intended to be achieved prior to the complementary optical tests.

II. Set-Up Environment

The experimental equipment set-up exploited for the electrical characterizations of SiPM detectors is one of the available facilities at the Catania astrophysical Observatory Laboratory for Detectors (COLD). It is a long time since COLD laboratory is concerned with detectors characterization [10]. In the recent

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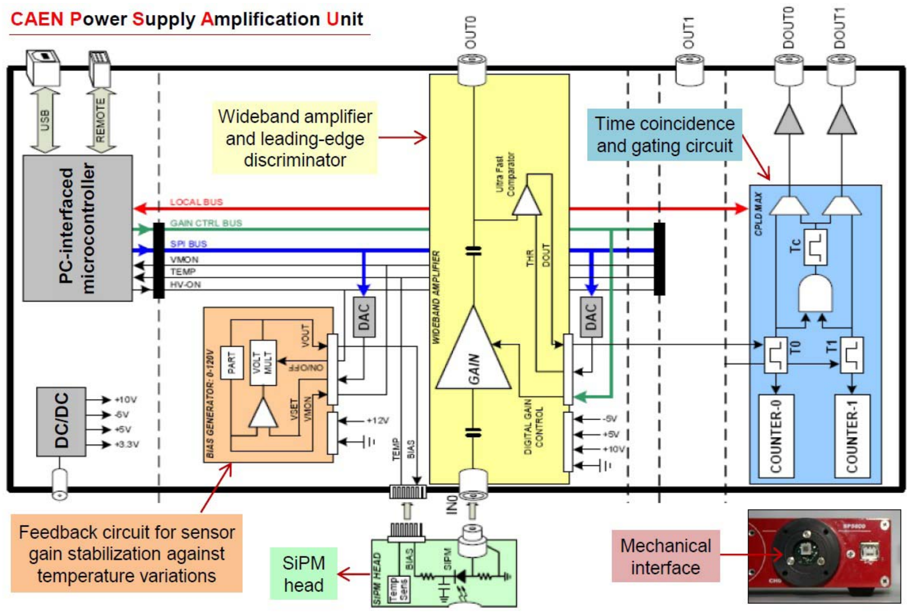

Fig. 1. Simplified electrical schematization of the CAEN power-supply/amplification unit used for the SiPM electro-optical characterization.

past various photon counting devices have been characterized, such as SPADs, SPAD arrays, and first generation SiPMs [10]–[14]. For each detector an appropriate instrumental apparatus, tailored for the specific device, has been arranged.

In the following, a brief description of the testing environment engaged for the electrical characterization is addressed.

A. Instrumental Equipment

The main instruments involved in the electrical experimental set-up are listed below:

- An Agilent 6634B DC power supply;
- A Keithley 487 picoammeter;
- A PicoQuant PDL 200-B pulsed diode laser;
- A CAEN SP5600 PSAU unit;
- A CAEN DT5720A 2-channel digitizer;
- A Tektronix FCA3000 frequency counter.

The Agilent power supply produces DC outputs with a 12-bit programmable resolution (<50mV) in the range of 0-100V. It is managed with an Agilent 82357-B USB/GPIB interface, and features a 16-bit measurement resolution (<12mV).

The Keithley ammeter is able to measure a current ranging from 2nA up to 2mA with a resolution down to 10fA. It is fully programmable via a GPIB (IEEE 488) standard interface.

The pulse generator is composed of a Picoquant PDL-200B controller and a Picoquant LDH-PC-405 laser head. The PDL 200-B is a pulsed diode laser driver unit, featuring controls for laser intensity and repetition frequency (8.0–0.5MHz), and providing a synchronization output for triggering other connected devices. The laser head has a wavelength emission in the range of 408–409nm, a maximum optical power of 0.250mW, and a minimum pulse width of 44ps, and is further equipped with an optical collimator. A mechanical adapter has been specifically realized to connect the laser head with the SiPM housing.

The CAEN PSAU is an electronic system embedding a power supply and a tunable amplification unit. It provides the cathode voltage for the SiPM detectors in a range of 0–120V with a 16-bit resolution, and features a variable amplification factor up to 50dB. It integrates a feedback circuit to stabilize the operating voltage (and, in turn, the sensor gain) against thermal variations and a leading edge discriminator feeding an internal counter. In addition, the system can provide a digital output with a tunable width from 20ns to 320ns. All parameters can be programmed and monitored via a standard USB interface. CAEN supplies a dedicated mechanical holder, integrating a temperature sensor with a 0.1 °C resolution, which is able to host different two-pin sensors. Moreover, an additional holder interface has been implemented to house the SiPM electrical board connected to the PSAU, which allows to keep the detector in dark condition and couple the whole system to various characterization setups. A mechanical cooling adapter has also been realized, allowing to operate the SiPM from room temperatures down to 10 °C. The simplified block diagram of the supply/amplification system is illustrated in Fig. 1, where the core functional blocks are highlighted.

The CAEN digitizer is sampled at 250MS/s by a 12-bit ADC, and can be programmed and monitored via a USB interface.

The Tektronix pulse counter features a 300-MHz counting rate with a 100-ps single-shot time and 3-mV resolution. It can be programmed and monitored via a GPIB standard interface.

All above-described instruments are PC-controlled by means of specific application software which is partly realized by the COLD group and partly supplied from the device vendors.

B. Experimental Set-Up

In this subsection, the apparatus setups for the SiPM electrical characterization measurements are described.

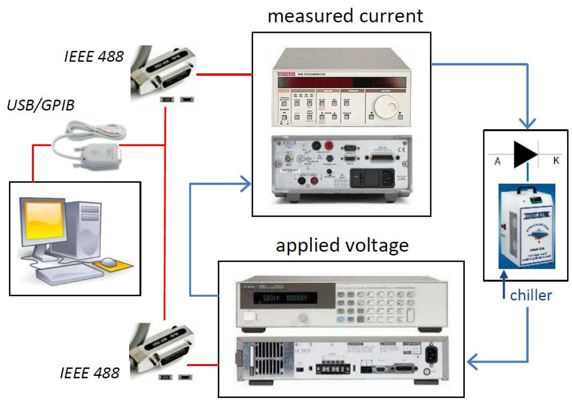

Fig. 2. Experimental apparatus used for breakdown voltage measurements with the traditional and derivative methods.

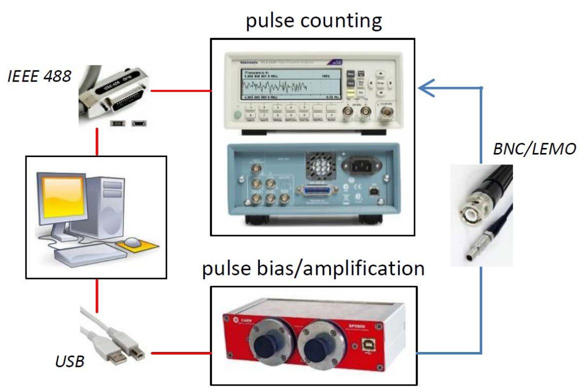

Fig. 3. Experimental apparatus used for breakdown voltage measurements with the dark count rate method.

The detector breakdown voltage can be determined, as later shown in the paper, through four basic methods. For the classical and derivative approaches, the testing apparatus is depicted in Fig. 2. The Agilent power supply provides the bias voltage to the detector, housed in a black box, and the Keithley ammeter, placed in series mode, reads the current flowing in the circuit. A specifically developed software allows to automatically tune the operating voltage, measure the reverse current and save all parameters into various format files for later processing.

Another simple method for the breakdown voltage estimation is the dark count rate method, and the experimental apparatus utilized for this test is shown in Fig. 3. The detector is connected to the CAEN PSAU and a mechanical housing keeps the SiPM in dark condition. The PSAU provides the operating voltage and amplifies the output pulses by a desired gain factor. The amplified signal then feeds the Tektronix counter, by which the dark count rate is determined. A software application allows to vary the bias voltage and acquire the relevant dark counts. All parameters data are stored for a later analysis.

The set-up used for the last method is basically the same as that exploited for the SiPM gain measurements, from which the breakdown voltage can be directly derived. The gain determination is accomplished through the set-up sketched in Fig. 4. The pulsed diode laser allows to illuminate the SiPM detector with a light source of adjustable intensity and duration. A mechanical adapter connects the laser head to the SiPM detector housed in the PSAU. The SiPM device is biased and its output signal is amplified and digitalized by the two CAEN systems, that are PC-interfaced and controlled by specific applications allowing to acquire the digital signals, trace charge histograms, and save all of the processed information.

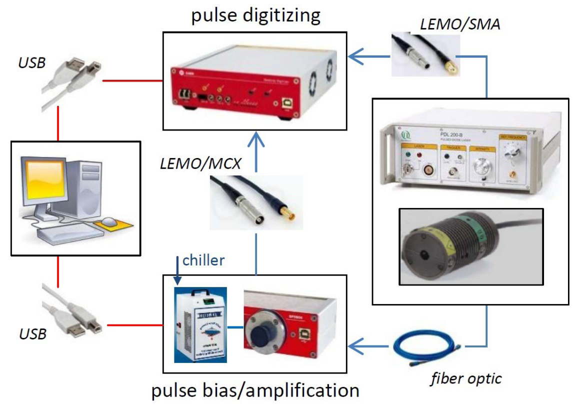

Fig. 4. Experimental apparatus used for gain measurements.

TABLE I
MAIN FEATURES OF THE TESTED SIPM DEVICES

	STM SPM-10H5 *(SPM-10H5-60)*	**Hamamatsu SN-1** *(S12572-050C)*
Active area	1.08×1.08 mm^2	3.0×3.0 mm^2
Microcells	324	3600
Pixel pitch	60 μm	50 μm
Fill factor	67.0 %	61.5 %

The measurement setups utilized to extract the SiPM electrical parameters are the same as those illustrated in Fig. 2, for the evaluation of the series photodiode resistance, and in Fig. 4, for the micropixel capacitance estimation.

Finally, electrical measurements as a function of temperature are also carried out through the same apparatus setups as shown in Fig. 2 and Fig. 4. To this purpose, a thermostatic camera has been realized to host the SiPM detector in adiabatic conditions, and a thermoelectric recirculating chiller has been exploited to cool the device and achieve the desired temperature.

III. ELECTRICAL CHARACTERIZATION

In this section the adopted testing methodology for achieving reliable electrical characterization measures is discussed.

The SiPM devices referenced throughout the section include some recently produced prototypes by different manufacturers which have been sent to our laboratories for testing and evaluation purposes (and thus are not commercially available), whose main basic features are summarized in Table I.

Due to the intrinsic complexity of the detector under test and to the measurement set-up implemented, a brief schematization of the characterization activity performed is dutiful. The procedure steps of the systematic methodology envisaged

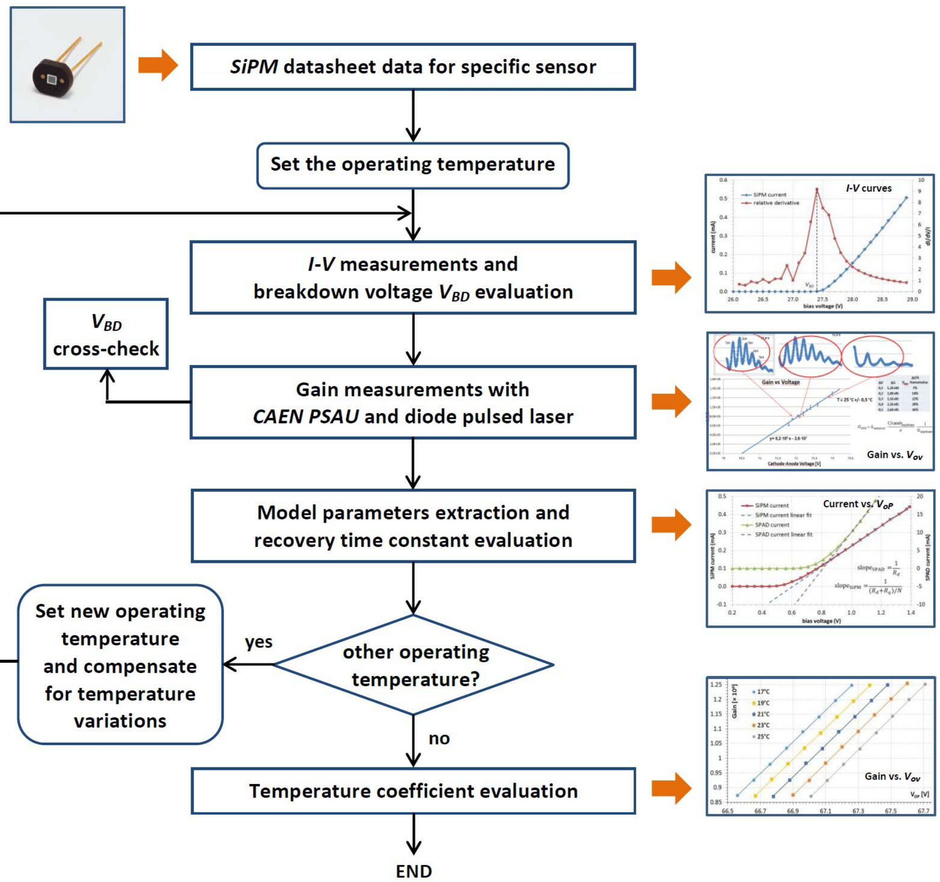

Fig. 5. Basic flow-chart representation of the adopted electrical characterization procedure for SiPM detectors.

to achieve accurate electrical characterizations are listed below:

- I–V measurements for the breakdown voltage estimation;
- Charge spectra analysis and gain measurements;
- Electrical parameters extraction and recovery time evaluation of the output pulses;
- Gain measurements vs. operating voltage at different temperatures, and thermal coefficient assessment.

The adopted electrical characterization procedure for SiPM detectors is illustrated in Fig. 5 in a flow-chart form.

A. Breakdown Voltage Assessment

The breakdown potential is defined as the bias point at which the electric field strength generated in the deplection region is sufficient to create a Geiger discharge.

As for common diodes, SiPM detectors can be biased both in forward and in reverse operation. The reverse I–V characteristic contains information on the breakdown voltage V_{BD}. It is worth remarking that, for a precise estimation of V_{BD}, measurements should be performed on a single SPAD microcell.

Typically, most device manufacturers supply only SiPM detector samples from different production batches, and specify a nominal breakdown potential in the relevant datasheets.

Concerning MPPC sensors, Hamamatsu does not provide the breakdown voltage for each device, while the operating

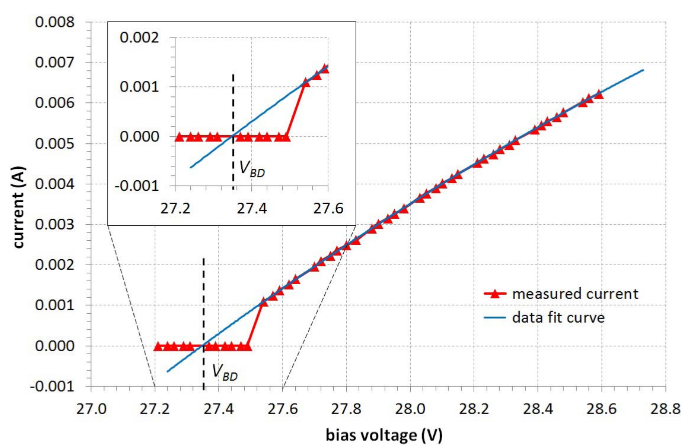

Fig. 6. Reverse I–V characteristics for the single STM SPAD device at room temperature around the breakdown potential.

voltage necessary to achieve a gain of 7.5×10^5 at 25 °C is given.

ST-Microelectronics SiPM detectors are provided along with the single photodiode element embedded in the same chips, so that accurate breakdown tests can be executed.

The breakdown potential is estimated based on a linear plot representation of the measured photodiode reverse current. The relationship between the reverse current of a basic STM SPAD microcell and the external bias voltage is depicted in Fig. 6 at a

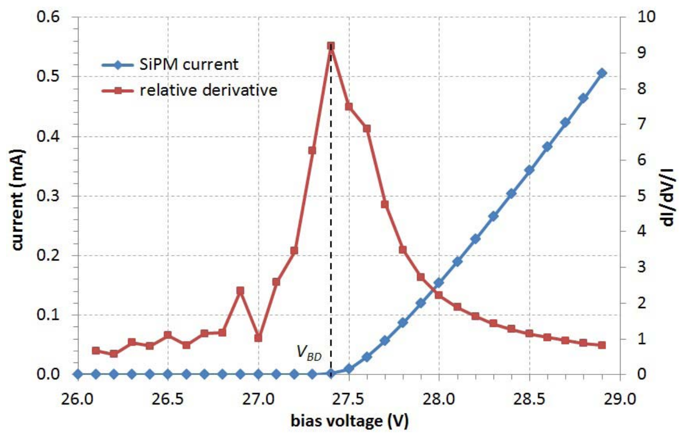

Fig. 7. Reverse STM SiPM current and relative derivative plots. The highest peak of the current derivative gives an estimation of the breakdown voltage.

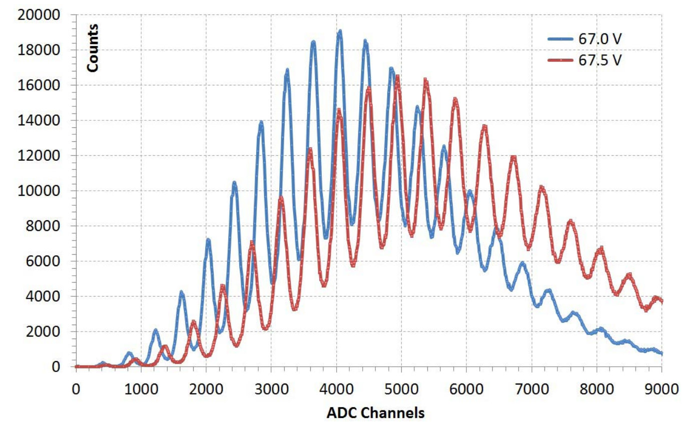

Fig. 8. Charge amplitude histograms for two different bias conditions at 23 °C for the Hamamatsu device.

fixed temperature. The curve plot is approximately constant up to the breakdown potential, beyond which the reverse current exhibits an increasing behavior. For a given temperature, V_{BD} is identified by the x-axis interception point of the data fit curve in Geiger-mode operation (27.35V in the specific case).

An alternative assessment of the detector breakdown, which is typically performed by Hamamatsu on MPPC devices, can be carried out from reverse I–V measurements by considering the highest peaking point in a current derivative plot as a function of the operating voltage, as that illustrated in Fig. 7 for the STM device, providing the maximum slope variation of the reverse current. As can be inspected, similar results are obtained when using the two different measurement approaches.

A useful tool for an independent estimation of the breakdown voltage, as shortly discussed, is the evaluation through the gain plot as a function of the bias voltage, in which the extrapolation of the x-axis intercept of the linear fit corresponds to the breakdown voltage extracted from the reverse I–V characteristics.

On the other hand, another important cross-checking for the assessment of the breakdown voltage can be achieved by means of the primary dark count rate as a function of the bias voltage, as shown in the second part of the manuscript, where the linear fit of the experimental data intercepts the x-axis at V_{BD}.

B. Gain Measurements

Gain tests are of crucial importance in computing the SiPM optical parameters; uncertanties on gain measurements directly affect the detector optical performance. Gain variations can also cause undesired shifts in the detected photo-peaks, which may compromise the energy resolution of the detection system.

The SiPM gain G is defined as the number of unit (electron) charges generated in response to a single-pixel photon absorption or thermally ignited avalanche. In Geiger-mode operation the multiplication factor of an avalanche discharge is expected to grow linearly with the operating voltage according to

$$G = \frac{Q_{TOT}}{q} = \frac{C_{pixel}\,(V_{OP} - V_{BD})}{q} \tag{1}$$

where Q_{TOT} is the total charge generated by a single avalanche discharge, C_{pixel} is the overall capacitance of the SPAD microcell, and q is the elementary electron charge.

The term in round brackets in equation (1), better known as overvoltage or excess bias voltage, V_{OV}, is critical in defining the major performance parameters of SiPM detectors.

In order to evaluate the detector gain at a given temperature for a defined range of bias voltages, the integrated charge values from the multi-channel analyzer are filled into charge amplitude histograms and the average spacing between two adjacent curve peaks is computed (in terms of ADC channels). Consequently, by accounting for the constant ADC rate (charge/channel), and scaling by the amplifier gain factor, the SiPM gain is obtained for a given bias voltage.

Gain measurements can be performed both in dark condition and in presence of illumination, since the signals triggered by an absorbed photon and those ignited by a thermally generated carrier are formally identical. However, in order to increase data statistics and improve precision, charge histograms are carried out upon illuminating the SiPM detector. In particular, for each performed acquisition, laser flux intensity and integration time windows are designed so as to achieve a large number of charge peaks with more than 10^4 occurrences.

Fig. 8 shows two charge pulse histograms of the Hamamatsu MPPC device at 23 °C and for two different operating voltages. Each observed peak corresponds to a specific number of fired pixels. Every pulse spectrum can be fit by a series of Gaussian distributions, with the μ parameter for each curve fit indicating the mean charge in the relevant peak and the σ parameter representing its width due to gain fluctuations and electronics noise. The photoelectron peaks are clearly visible, demonstrating an identical performance of the single microcells and an excellent photoelectron resolution of the MPPC device.

The average spacing between two consecutive charge peaks almost linearly increases with the bias conditions. All gain data points in a defined range of operating voltages are collected in Fig. 9 for the same detector and equal working temperature. As shown in the inset plots for two different V_{OP} values, the curve peaks mutually enlarge with increasing operating voltage.

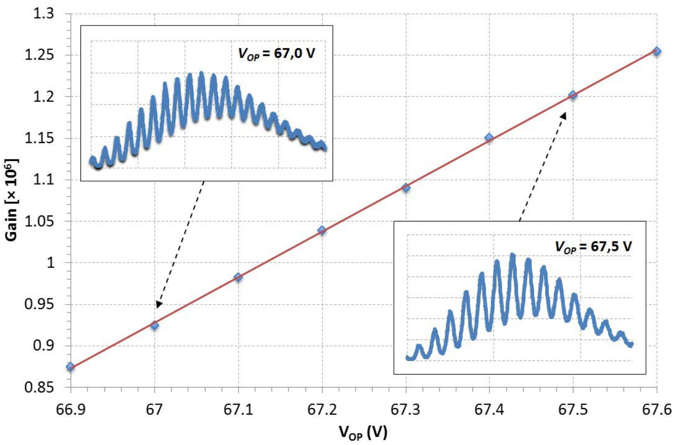

Fig. 9. Gain measurements as a function of the bias voltage for the Hamamatsu device. The linear fit allows to extrapolate the breakdown voltage.

From the slope of the linear fit the gain sensitivity with respect to the operating voltage, dG/dV_{OP}, can be achieved.

The extrapolation of the x-axis intercept of the linear fit in a gain plot as a function of the bias voltage provides an indirect estimate of V_{BD} (66.2V for the MPPC device), and therefore represents an important validation tool for the effectiveness of measurement and data handling protocols adopted.

C. Model Parameters Extraction

The availability of accurate electrical models can refine and enrich the knowledge of the design and behaviour of the SiPM detector as a signal source, allowing a reliable interpretation of its static and dynamic features as well as its physical interaction with the coupled front-end electronics. Thanks to these models, useful circuit-level simulations can be carried out on the SiPM detector system coupled to the front-end electronics, and hence the major characteristics of the obtained signal waveforms can be conveniently related to the model parameters. Of course, the effectiveness of simulations depends on the choice of the circuit parameters, whose experimental extraction procedure therefore assumes a significant role in demonstrating the predictive capabilities of the adopted model.

The SiPM model parameters that can be extracted according to the adopted electrical characterization procedure include the microcell quenching resistance R_q, the photodiode breakdown potential V_{BD} and internal resistance R_d, and the overall pixel capacitance $C_{pixel} = C_d + C_q$, including the two contributions of the junction capacitance of the diode deplection region, C_d, and the parasitic stray capacitance of the quenching resistor, C_q. Based on the model parameters obtained and accounting for the total number of microcells N of which the device is composed, the most peculiar features of the SiPM output transient signals can be straightforwardly derived.

The forward I–V characteristics of the SiPM detector present two distinct parts: an initial phase when the current is governed by the diode exponential behavior, and a second phase in which the quenching resistor becomes the dominant contribution and limits the forward current to a linear growth.

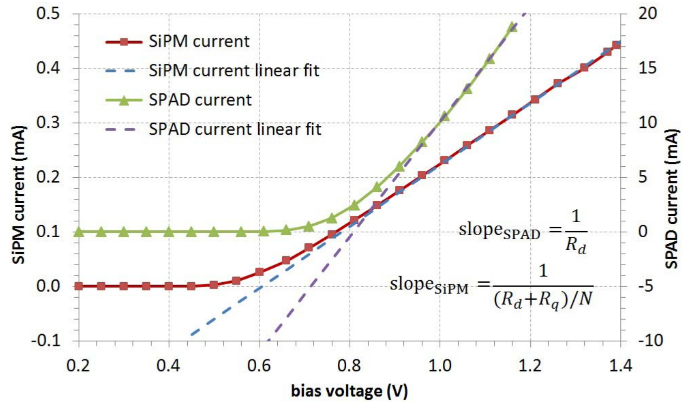

Fig. 10. Forward I–V measurement plots for the STM SiPM detector and for the relevant single SPAD microcell.

From the slope of the linear part the equivalent series resistance $(R_d + R_q)/N$ can be evaluated, and since $R_d \ll R_q$, the dominant contribution of the quenching resistor can be extracted.

As to the photodiode inner resistance R_d, since a direct measurement of the voltage drop across the diode terminals within an individual microcell is not feasible, a realistic extraction of the value of R_d is prevented, unless the basic SPAD element is also provided by the device manufacturer. By that means, in the absence of the integrated quenching resistance, the slope of the forward I–V functions of the single microcell is purely dictated by the inner diode resistance, whose value is thus extractable.

For illustration purposes, the forward I–V measurements for the STM SiPM detector and the relevant results for one of its basic SPAD microcells are shown in Fig. 10, where the physical dependences of the linear slopes on the internal photodiode and quenching resistances are also outlined.

The overall microcell capacitance C_{pixel} can be extracted by the slope of the linear fit in a gain plot vs. operating voltage as that reported in Fig. 9, according to equation (1). The estimated values of C_{pixel} for the characterized detectors are found to be consistent with the global output device capacitances provided in the manufacturers' specification documents.

The detector output pulse signal is expected to exhibit a very fast leading edge in the order of few hundreds of picoseconds, determined both by the avalanche spreading and by the diodes equivalent capacitance discharge, and a slow exponential decay governed by the recharging time constant, τ_r, that is nominally expressed by the product of the equivalent quenching resistance and overall micropixel capacitance

$$\tau_r \approx R_q \left(C_d + C_q\right) \tag{2}$$

Time constant τ_r is considered as one of the most significant parameters of the SiPM response, since it defines the recovery time of its basic microcells. In fact, the photodiode voltage takes nearly $5\tau_r$ to recover the correct bias conditions within 1% of the final value, and any incoming photon arriving prior to this time, which can be ranged in the order of microseconds, has a lower avalanche triggering probability. The SiPM recovery time therefore gives important indications

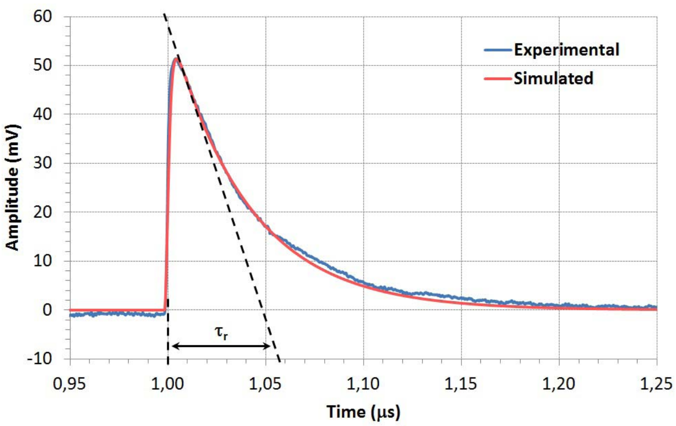

Fig. 11. Simulated and experimental output signal waveforms on a 50-Ω load resistor for the Hamamatsu MPPC device under a single firing cell.

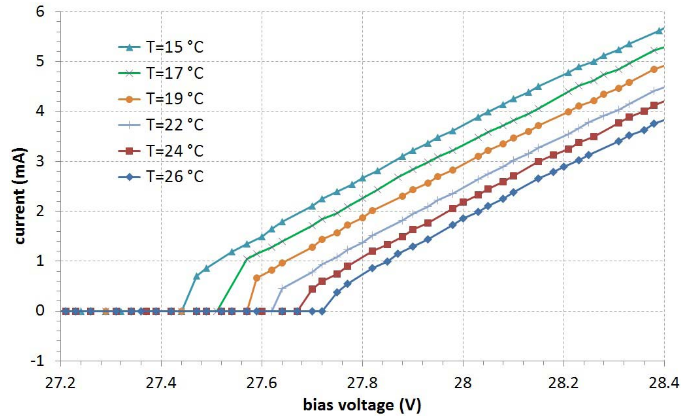

Fig. 12. Reverse current plots of a basic STM SPAD microcell as a function of the applied voltage at different operating temperatures.

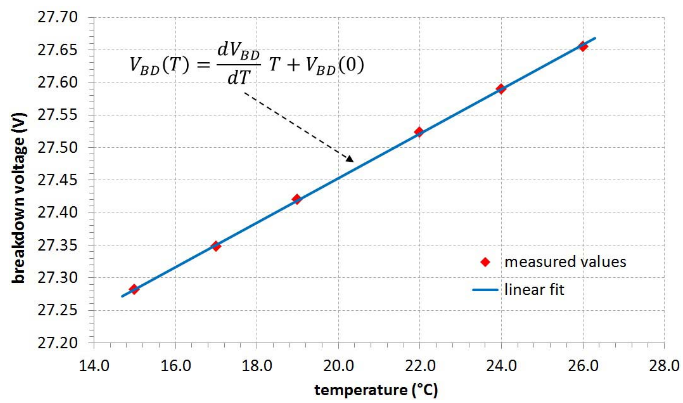

Fig. 13. Breakdown voltage variations of the single STM SPAD microcell as a function of temperature and relevant thermal coefficient evaluation.

on the maximum allowed photon rate in case of constant light illumination.

Exploiting the extracted values of both quenching resistance and micropixel capacitance, a useful assessment of the recovery time constant of the SiPM output pulses can be achieved.

By way of illustration, Fig. 11 shows the experimental waveform of the MPPC output pulse along with the simulated SPICE signal resulting from the relevant electrical model in [9], which also accounts for the CAEN pre-amplifier model. The recovery time constant obtained (∼58ns) is compatible with (2).

Finally, the single pulse output transient response also allows an independent assessment of the SiPM gain, which can be determined by integrating the single pixel current signal over the entire pulse duration, yielding the total charge Q_{TOT} released by the trigger event [15], and dividing by the elementary charge q, in keeping with (1). As an example, integrating the simulated single photoelectron output current pulse of the MPPC detector at $V_{OP} = 67.5$V yields a SiPM gain value of $\sim 1.2 \times 10^6$, which is consistent with the relevant data in Fig. 9.

D. Temperature Characterization

For several SiPM applications, drifts of the detector electro-optical parameters related to thermal excursions may represent a severe limitation issue that strongly prevents from achieving optimal device performance. The most crucial cause of drifts in the SiPM performance parameters due to thermal fluctuations is the sensible temperature dependence of the breakdown voltage V_{BD}. The thermal effects on V_{BD} should be accurately known to correctly predict the static and dynamic behavior of the SiPM detector at different operating conditions.

For pure avalanche breakdown phenomena, the photodiode breakdown voltage dependence on temperature is expressed by the following approximated relationship

$$V_{BD} = V_{BD0}\left[1 + \beta\,(T - T_0)\right] \tag{3}$$

in which V_{BD0} is the breakdown potential at room temperature, T_0, and β is the linear growth constant that is typically ranged in the order of magnitude of $10^{-3\circ}C^{-1}$, depending on silicon doping concentrations.

A qualitative explanation of the breakdown voltage increase with temperature relies on the fact that those hot charge carriers crossing the photodiode deplection layer under a high applied electric field tend to lose part of their kinetic energy in optical photons through lattice scattering, hence resulting in a smaller ionization rate; as a consequence, the carriers must overcome a greater potential difference or a higher applied voltage to gain sufficient energy for the generation of an electron-hole pair and the consequent ignition of the avalache discharge current.

Characterization measurements of the temperature sensitivity of the breakdown voltage, which is variable considering different SiPM manufacturers and different lots of production, can be carried out from reverse I–V measurements on single SPADs.

Fig. 12 shows the measured reverse current of the STM single microcell for different values of the operating temperature. As predicted, the current curves are shifted to the right side of the I–V plane with increasing temperature as a direct result of the higher breakdown voltage. In Fig. 13 the measured V_{BD} values are plotted as a function of temperature, and the corresponding thermal coefficient, dV_{BD}/dT, is simply

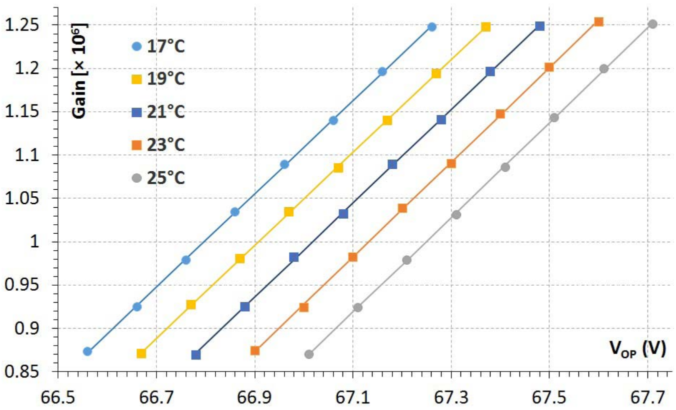

Fig. 14. Gain measurements on the Hamamatsu MPPC device as a function of the operating voltage at different temperatures.

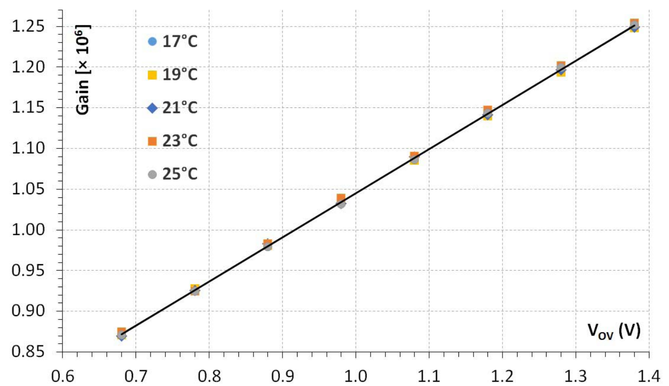

Fig. 15. Gain fluctuations for the Hamamatsu MPPC device as a function of overvoltage at different temperatures.

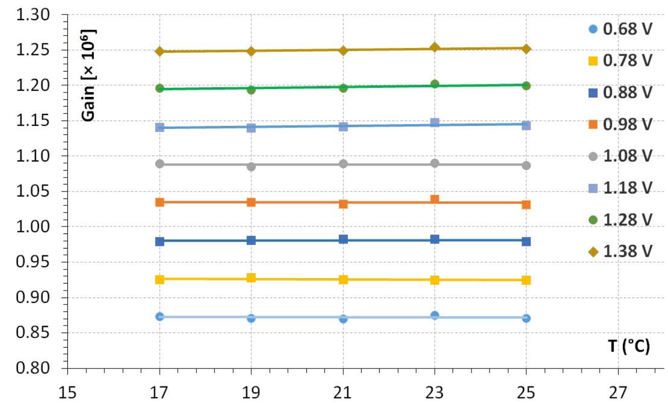

Fig. 16. Gain fluctuations for the Hamamatsu MPPC device as a function of temperature at different overvoltage.

derived from the slope of a linear fit to the measured data. The obtained value in Fig. 13 (~34mV/°C) is compatible with the relevant data provided in the SiPM manufacturer's datasheet.

The detector gain G is not directly related to the temperature T. Its value decreases with increasing temperature as a result of the increase in the breakdown voltage, which is a linear function of T, in keeping with relationship (3). Fig. 14 depicts the gain behavior of the Hamamatsu MPPC device as a function of the operating voltage at different temperatures. SiPM gain compensation is efficiently exploited to maintain constant overvoltages at different temperatures. A linear gain dependence in the range of interest is clearly observable, and temperature variations do not sensibly affect the slopes of the interpolated curve fits.

V_{BD} extrapolations of the linear fits in a gain plot vs. V_{OP} at different temperatures (as in Fig. 14) allows for an independent estimation of the thermal coefficient obtained from reverse I–V measurements (as in Fig. 12) in a different fashion. For the MPPC device, a thermal coefficient of ~57mV/°C is obtained with both methods.

Fig. 15 reports the measured gain variations with the applied overvoltage V_{OV} at different temperatures, from which a global linear behaviour independent from temperature is still recognizable. The same gain measurements are presented in Fig. 16 as functions of temperature for different overvoltage values, where the linear fits for each fixed overvoltage value are found to have marginal angular coefficients.

Fig. 15 and Fig. 16 demonstrate that SiPM gain fluctuations with temperature are dominated by the temperature dependence of V_{BD}. As expected, no significant gain variations are detected at different temperatures for a fixed overvoltage.

Regardless of costant overvoltage, however, a change in temperature directly affects the dark count rate of SiPM detectors, which represents the most important source of noise in this kind of devices, as discussed in the second part of the paper.

Therefore, as a general remark, since temperature variations have great impact on the main SiPM electro-optical features, the importance of stabilizing the detector temperature or providing operating voltage compensation versus temperaure variations is essential for measurements reliability.

IV. Conclusion

A systematic and detailed characterization methodology for SiPM sensors is discussed, with the aim of providing accurate measurements of the most significant electrical parameters and qualifying the overall device performance. The procedure steps followed along with the extensive analyses performed have led to a standardization of the adopted testing methodology, so as to be efficiently applicable to every kind of solid-state sensors. A few recently produced SiPM detectors are analyzed and their main electrical characteristics are estimated, in order to confirm the effectiveness of the envisaged protocols and data-handling procedures in providing a reliable characterization of the SiPM detectors. All evaluated characteristic trends are found to show a good agreement with the expected behavior from the physics theory of the device.

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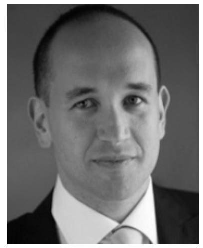

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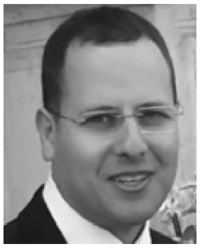

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