Characterization of a Novel 100-Channel Silicon Photomultiplier—Part I: Noise

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***Abstract*—In this paper, we present the results of the first noise characterization performed on our novel 100-channel silicon photomultiplier. We have improved our previous single-photon avalanche photodiode technology in order to set up a working device with outstanding features in terms of single-photon resolving power up to $R = 45$, timing resolution down to 100 ps, and photon-detection efficiency of 14% at 420 nm. Tests were performed, and features were measured, as a function of the bias voltage and of the incident photon flux. A dedicated data-analysis procedure was developed that allows one to extract at once the relevant parameters and quantify the noise.**

***Index Terms*—Afterpulsing, dark noise, gain, quantum detection efficiency, quenching resistor, silicon photomultiplier (SiPM), single-photon avalanche photodiode (SPAD), single-photon counting.**

I. Introduction

PHOTON handling is nowadays considered an emerging issue, with many possible applications, particularly in the wide field of sensors and related transducers [1]. In the last few years, a new kind of planar semiconductor device has slowly but steadily come out, namely the silicon photomultiplier (SiPM), with promising features that, in some respect, could even replace traditional photomultiplier tubes [2]. Based on a Geiger-mode avalanche photodiode elementary cell [3], it consists of an array of n independent identical microcells whose outputs are connected together. The final output is thus the analog superposition of n ideally binary signals [4]–[6]. This scheme, along with the sensitivity of each individual cell to single photons, appears to result, in principle, in the perfect photosensor capable of detecting and counting single photons in a light pulse.

Unfortunately, this is not the case, considering that this kind of device has several drawbacks and all of them are mainly derived from its noise features; due to lattice defects and impurities in the basic material, the dark counts cannot be reduced below a given rate, and as these mainly have a thermal origin, one could be tempted to solve the problem by cooling the device itself. This works to a given extent; however, another problem sets in, namely afterpulsing, due to charge carriers trapped within the semiconductor during the avalanche signal and later exponentially released. Cooling the device results in an increase of the exponential decay constant, and therefore, the lowest operating temperature becomes a tradeoff between random thermal counts and long-lasting afterpulse counts [1]. This could represent an intrinsic limitation to the implementation of large-area SiPM detectors, if one actually needs the single-photon sensitivity. Nonetheless, the suitable use of SiPMs depends strongly on a particular application; although dark counts are a problem for low-level light applications, if there is ample light, one can set the threshold at several photoelectrons and thus suppress them. Such a tradeoff can be useful to optimize the energy resolution.

Therefore, although not capable of totally replacing the traditional photomultiplier tubes, the SiPM already promises to fulfill a wide set of requirements coming from numerous applications. This is why many groups and companies are currently pursuing the development of large-area SiPMs [7]–[15].

In previous papers, we described our development and test of single channels and arrays of 5 × 5 single-photon avalanche diodes (SPADs) operating at low voltage and fabricated in silicon planar technology [17]–[19]. In this paper, we will illustrate our novel 10 × 10 SiPM and its characterization in terms of bias voltage and noise; the charge resolution, time resolution, and photon-detection efficiency (PDE) will be illustrated in the second part. We will show that the device performance is indeed outstanding, although it still represents the first-generation prototype and other better performing sensors are already under production.

II. Sensor Description

Our SiPM is based on a SPAD cell that is a p-n junction operating in Geiger mode at a low voltage (≈30 V) and fabricated in silicon planar technology. The junction is biased slightly above the breakdown by an overvoltage around 10% of the breakdown voltage itself, and it remains quiescent until a photon is absorbed in the depletion volume. This gives rise to the development of an avalanche current pulse, which needs a dedicated circuit to quench it, whose total charge is independent of the number of initial photocarriers. The quenching circuit we chose

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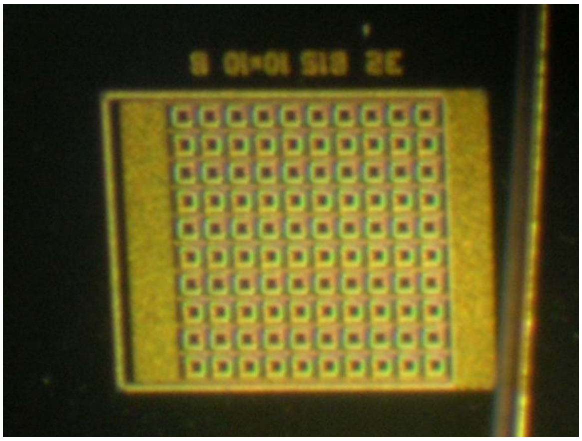

Fig. 1. Microphotograph of the 10 × 10 SiPM with 50-μm pitch. Each cell's active area, 30 μm wide, appears in the picture as a light transparent polysilicon resistor frame surrounding a darker central spot.

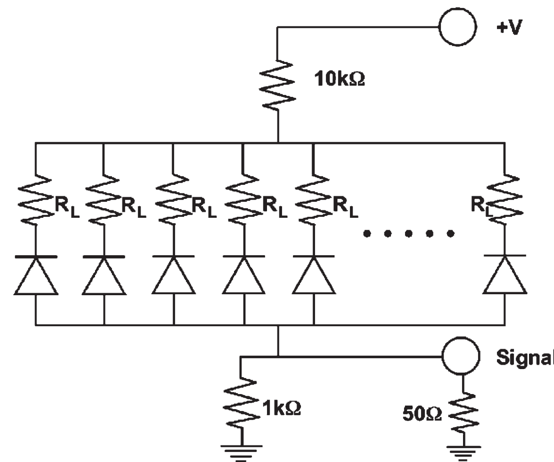

Fig. 2. Electrical schematic of the SiPM, its biasing circuit, and output signal extraction.

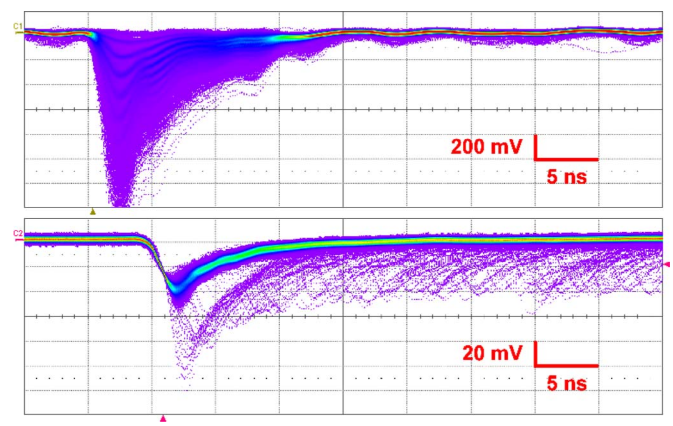

Fig. 3. Snapshot of SiPM persistence plots on a digital scope. (Upper plot) Low-light-level pulses generated by a laser produce the typical equally spaced electrical signals corresponding to discrete numbers of photons detected. (Lower plot) Dark counts basically show up as one-cell pulses.

to employ is a passive one (a large-value resistor), which allows us to keep the overall circuitry very simple. Such a resistor, in the form of a transparent polysilicon square frame, was integrated on top of the cell's cathode. The cell is square-shaped, with a 50/30 μm side-over-active-area ratio and a resulting 36% fill factor (the active area also includes the polysilicon frame). We also deposited an antireflective coating layer and reduced the quasi-neutral region thickness above the thin junction depletion layer, in order to enhance the spectral response in the blue and near-ultraviolet wavelength ranges. The expected consequences are low leakage currents, low noise, and good PDE [20].

By replicating this elementary cell, we produced a SiPM made of a 10 × 10 array with common anode, shown in Fig. 1, whose test results will be described in the following. Each cell has a breakdown voltage of around 29.5 V at room temperature, with a variation coefficient of 35 mV/°C. Each elementary cell is surrounded by a suitable trench filled with opaque material, in order to drastically reduce the probability of optical crosstalk between neighboring cells. For our tests, the SiPM was biased at voltages between 31.5 and 33 V, and the output signal was extracted based on the simple scheme shown in Fig. 2. A snapshot of persistence plots taken on a digital scope is shown in Fig. 3, where the (upper plot) low-light-level pulses, generated by a laser, produce the typical equally spaced electrical signals corresponding to discrete numbers of photons detected. The signal rise time is below 2 ns; its duration is 10 ns. The dark-count signals, shown on the lower plot, basically show up as one-cell pulses. This indicates a very low crosstalk level. Afterpulses show up as a band at the one-cell amplitude level.

III. Testing Environment

The experimental apparatus we exploited for our tests includes the following:

1) HP 6625A power supply for biasing the sensor;
2) 671-nm pulsed laser with fiber output and FWHM pulsewidth of 40 ps;
3) standard NIM electronic modules:
   a) TTL-NIM-ECL level adapters;
   b) Lecroy 4608 leading edge discriminator;
   c) Ortec CF8000 constant fraction discriminator;
   d) Ortec 934 constant fraction discriminator;
   e) Lecroy 222N gate and delay generator;
   f) Lecroy 428F linear fan-in fan-out;
   g) Lecroy 429A logic fan-in fan-out;
   h) fast amplifier, namely FTA810B, with gain 200 and rise time below 1 ns;
   i) fast counter timer, namely Tennelec TC535P.
4) fast counter–timer computer board, namely National Instruments 6601;
5) time-to-amplitude converter (TAC), Ortec 457;
6) cable delay units;
7) Silena 4418/Q CAMAC charge-to-digital converter;
8) Silena 4418/T CAMAC time-to-digital converter;
9) Silena 4418/V CAMAC voltage-to-digital converter;
10) small multiparameter data-acquisition system developed at LNS.

The following four basically different kinds of measurements were performed: counting (for simple dark-count measurements) shown in Fig. 4; self-correlated timing (for afterpulse measurements) shown in Fig. 5; self-triggered charge integration (for noise measurement) shown in Fig. 6; and charge and

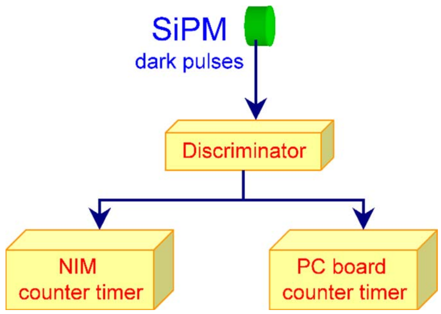

Fig. 4. Sketch of the electronics for the counting setup, employed for dark-count measurement.

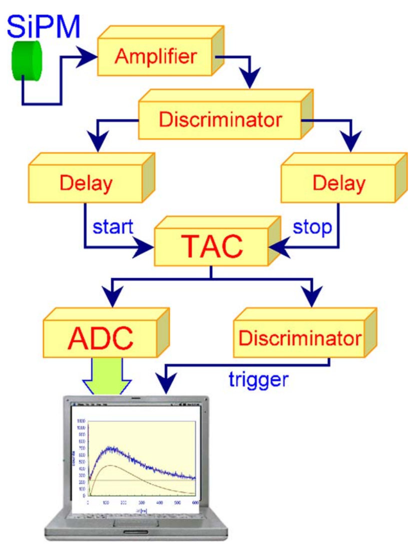

Fig. 5. Sketch of the electronics for the self-correlated timing, employed for afterpulse measurements.

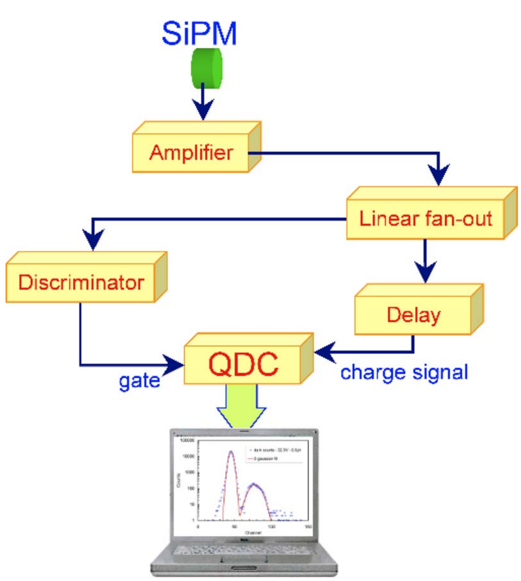

Fig. 6. Sketch of the electronics for the self-triggered charge-integration noise measurements.

time (for SiPM response characterization), which will be described in the second part. We remark that the actual configuration of the electronics was slightly modified and fine-tuned with respect to what is shown in the figures based on specific needs.

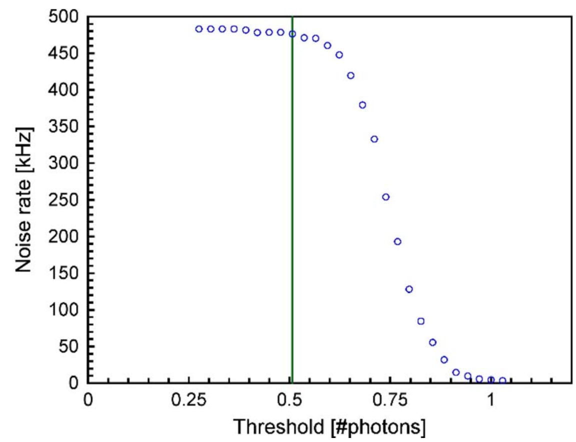

Fig. 7. Measured noise rate as a function of the discriminator threshold at a 32.5-V bias. The threshold is normalized to the one-photon signal amplitude.

We decided to perform all our tests at four different bias voltages, namely 31.5, 32, 32.5, and 33 V, as we saw that below 31.5 V, the gain is rather low and the electronic noise level becomes dominant, whereas beyond 33 V, the dark-count rate becomes hardly acceptable.

The charge and timing characterizations, as well as the PDE measurements, were done at room temperature, as the breakdown voltage increases rather slightly with the temperature (35 mV/°C) [20]. This reflects into the nice charge resolution that will be shown in part 2. Unfortunately, this is not the case with noise because, due to its intrinsic exponential nature, it depends strongly on the temperature. Therefore, the noise characterization was done at stable temperature (19 °C) by means of a liquid cooling system.

IV. Dark-Count and Afterpulse Measurements

In order to evaluate the dark-count rate of the device being tested, we placed it onto a thermally stabilized copper plate into a light-tight box. Then, using the electronic setup shown in Fig. 4, we counted the number of noise pulses generated per unit time as a function of the discriminator threshold. We employed two different independent counters simultaneously, in order to make sure that there was no systematic error introduced by the counter itself. The observed count rates on the two counters differed by less than 1% in all measurements. Fig. 7 shows the resulting plot for the bias value of 32.5 V; the threshold was normalized to the one-photon signal amplitude. As shown in the plot, using a threshold value corresponding to 1/2 of the one-photon signal amplitude does not cut significantly the one-photon signal. From then on, we decided to perform all the noise measurements with such a threshold value, which will be referred to as 0.5 ph.

Fig. 8 shows the (squares) measured noise rate as a function of the bias voltage. We remark that these counts eventually include afterpulses and pulses generated by crosstalk [3], [16], [21]–[23]. In order to evaluate their amount and contribution to the real signals, we needed a measurement procedure. We therefore employed a TAC with a range tunable between 50 ns and 5 μs. We measured the time distribution of afterpulses in a full range of 5 μs with the following method. The signal from

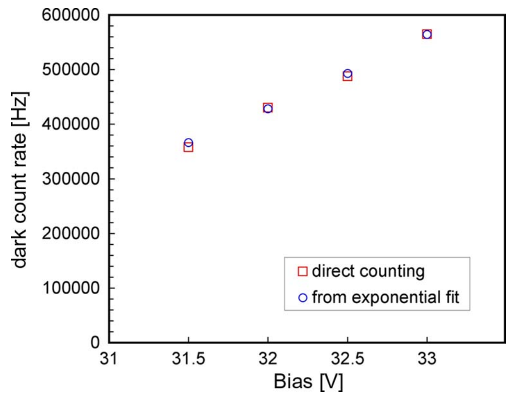

Fig. 8. Noise rate as a function of the bias voltage at a 0.5-ph threshold. The square symbols are the values measured with the counting system of Fig. 4; the circles are the values deduced from the exponential slopes measured with the setup of Fig. 5.

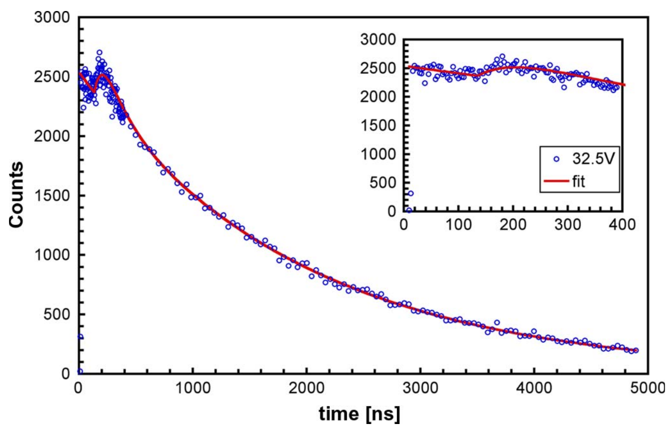

Fig. 9. Distribution of the (open circles) time interval between two consecutive signals and a (solid line) fit with the function (1) described in the text. The inset is a zoom of the 0–400-ns region.

the SiPM was fed into a Lecroy 4608 discriminator operating at a threshold of 0.5 ph. Two fast logic outputs were derived from this discriminator and then suitably delayed, with one used as the start to the TAC and the other one as the stop (Fig. 5).

By changing the delay values, we were able to perform a precision calibration of the time scale, exploiting known delays between the start signal and its delayed copy. After calibrating the system, we chose the delay configuration so that the self-coincidence peak resulted below the overall TAC threshold. This way, the system was only triggered whenever, following the main signal, there was another pulse between 50 ns and the full time range. We thus measured the distribution of time intervals between two consecutive signals.

As the attainable dynamic range was limited, we decided to explore the 0–400-ns region in more detail, in order to be able to observe any structure due to fast afterpulsing. We found, indeed, that this was the case. We employed the same setup and procedure; only the TAC range was changed to 400 ns. After proper normalization, we were able to join the two spectra taken at different time ranges (and resolutions). A sample histogram for the 32.5-V case is shown in Fig. 9, along with a data fit, based on the function of (1). The first two points, strongly affected by the combined effect of three thresholds

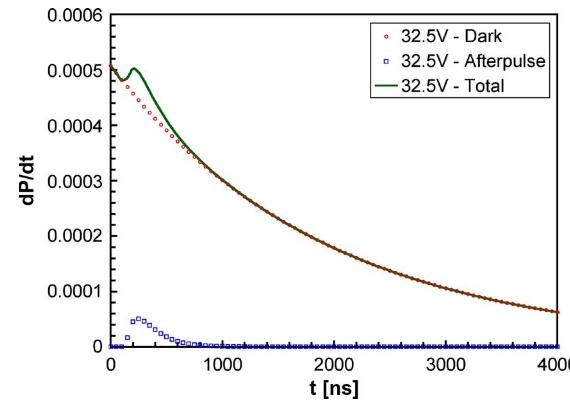

Fig. 10. Probability distribution of the time interval between (solid line) two consecutive signals with the contributions due to the (open circles) dark counts and to the (open squares) afterpulses.

(discriminator, TAC–ADC, and trigger to the data acquisition system), were not included in the fit

$$F(t) = A_{\text{dark}} \cdot e^{-\frac{t}{\tau_{\text{dark}}}} + [t > t_{\text{thr}}] \cdot A_{\text{AP}} \cdot \left(1 - e^{-\frac{t-t_{\text{thr}}}{\tau_R}}\right) \cdot e^{-\frac{t-t_{\text{thr}}}{\tau_{\text{AP}}}}. \quad (1)$$

The fit parameters relevant for our device are as follows:

1) A_{dark} and A_{AP}, representing the weights of the pure dark counts and of the afterpulses, respectively;
2) τ_{dark} and τ_{ap} representing the time constants of the two previous processes;
3) τ_R, i.e., the recharging time constant of the firing cell;
4) t_{thr}, representing a time offset due to afterpulse signals from the fired cell occurring while it is recharging but whose amplitude is still below the threshold.

All our fits reproduced nicely the experimental data, with χ^2/NDF values in the range 1.00–1.18, and this gave us confidence to use the resulting parameters in order to estimate the probability of random dark counts and correlated afterpulses.

In Fig. 10, an example of the normalized probability that a second signal occurs at a given time t is shown, along with the separate contributions due to dark counts and afterpulses, as deduced by the fit parameters for the SiPM biased at 32.5 V. We observe that the probability of afterpulsing is already small at 1000 ns. To better quantify the effective contribution of afterpulses to the sensor behavior, Fig. 11 shows the (solid line) integrated probability that a second signal occurs after a given time t_0, again with the (open circles) separate contributions due to the dark counts and to the (open squares) afterpulses. This afterpulse probability is on the order of a few percent at all bias values, drops well below 1% after 500 ns, and becomes negligible after 1000 ns. Its overall values at the four bias voltages are reported in Table I, along with the parameter values resulting from the fits and additional relevant numbers. We remark here that although χ^2/NDF is not strongly sensitive to the particular values of τ_{ap} and τ_R, it is indeed sensitive to the overall contribution of the afterpulsing (i.e., the area of the corresponding bump around 100–200 ns on the spectrum in Fig. 9).

The noise probability distribution obtained from the fits can be immediately used to provide an estimate of the noise rate,

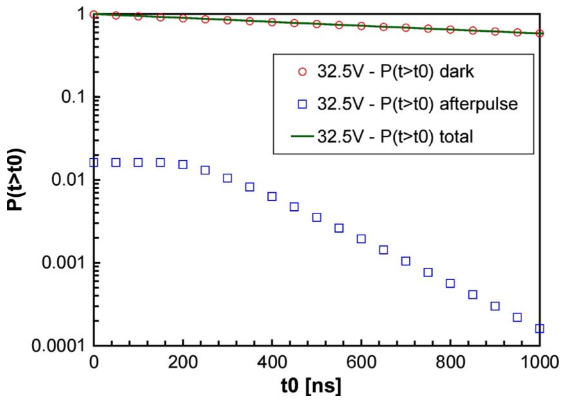

Fig. 11. Probability of occurrence of a second signal (solid line) after a given time t_0, (open circles) with the contributions due to the dark counts, and (open squares) to the afterpulses.

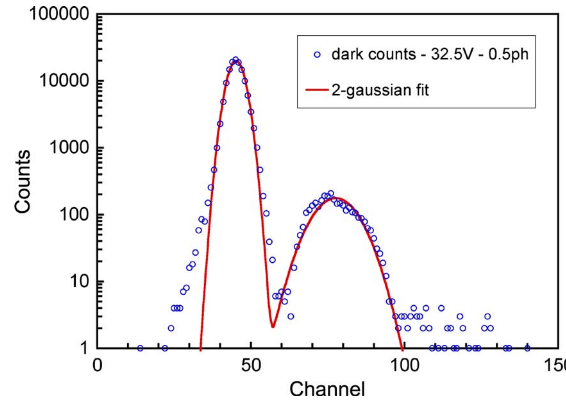

Fig. 12. Example of charge spectrum of the self-triggered noise at 0.5-ph threshold and at 32.5-V bias voltage. The y-axis scale is logarithmic.

TABLE I
SIPM NOISE BEHAVIOR: RESULTING FIT PARAMETERS AND OTHER RELEVANT NUMBERS AT THE FOUR EXPLORED BIAS VOLTAGES (SEE TEXT FOR DETAILS)

Bias [V]	31.5	32	32.5	33
Noise rate [Hz] (direct count)	366508	428115	493091	564548
A_{dark}	1617	2253	2539	3664
τ_{dark}[ns]	2657	2219	1914	1653
A_{AP}	950	997	1003	1498
t_{thr}[ns]	138	105	134	116
τ_R [ns]	281	155	156	107
τ_{AP} [ns]	122	154	158	139
Noise rate [Hz] (evaluated)	357619	430119	487902	564991
$\chi 2$ / NDF	1.000	1.000	1.000	1.179
P(noise in gate) gate width=45ns	0.017	0.020	0.023	0.027
P dark	0.992	0.985	0.984	0.981
P afterpulse	0.008	0.015	0.016	0.019

which can be checked against the values measured by means of direct counting. These values, shown in Fig. 8 (circles) and in Table I, give us confidence on the correctness of the whole procedure, as they lay very close to the measured ones.

We present a rough numerical calculation, in order to provide a qualitative explanation of these numbers. The average time between two noise events, as computed from the distribution shown in Fig. 10, is on the order of 2000 ns, which implies an average noise pulse rate of about 0.5 MHz. Assuming an $\approx$50-ns duration of the signal integration gate (rather reasonable if using the SiPM to detect photons from fast plastic scintillators or dye lasers), this gives rise to a noise-free duty cycle of about 97.5%. In the remaining $\approx$2.5% of cases, we expect to have noise contamination, i.e., one additional pixel fired in the SiPM (or a charge corresponding to a fraction of a pixel, in case it occurs across the edge of the integration gate or in case it occurs in a pixel that is recharging after a previous pulse). Moreover, the afterpulse probability distribution is such that at an input signal average rate on the order of <1 MHz, it can be neglected.

In order to gather further evidence of the correctness of the aforementioned results on noise, we performed another set of measurements exploiting charge integration [24]. Using the setup shown in Fig. 6, we measured the charge spectrum of noise events. The gate signal, thus self-triggered at a 0.5-ph threshold, had a duration of 45 ns. During this time, we expected to integrate the charge due to the triggering signal (one-photon equivalent) plus any additional signal that possibly occurred within the gate. For each bias voltage, we collected a spectrum such as that shown in Fig. 12. Apart from effects due to the threshold (left-hand-side shoulder on the first peak) and to signals occurring across the closing edge of the gate (bump and left-hand-side broadening of the second peak), which are not relevant to the results and which we will not discuss here, the area of each peak is proportional to the probability of occurrence of single- and double-noise counts within the gate duration. We do not know the proportionality constant, which, however, could be computed by keeping into account the dead time of the data-acquisition system. Nonetheless, if there is no relevant correlated afterpulsing probability, as we know to be the case within 45 ns, the probability of a double-noise count is simply the square of the single one. Therefore, the ratio of the two areas should, in a straightforward manner, provide the single probability we are after.

We fitted the spectrum with a two-Gaussian function and then used the resulting parameters to evaluate the areas and their ratio analytically. At the same time, we computed the ratio in a numerical fashion by simply summing the counts under the two peaks of the spectrum. In parallel, we inferred the same probability by using the time distribution probability of noise (Figs. 9 and 11) and the gate width of 45 ns. The probability values obtained with the three methods for each bias value, shown in Fig. 13, are very close to each other and show the same behavior with the bias voltage. This agreement provides additional evidence of the correctness of our measurements and method.

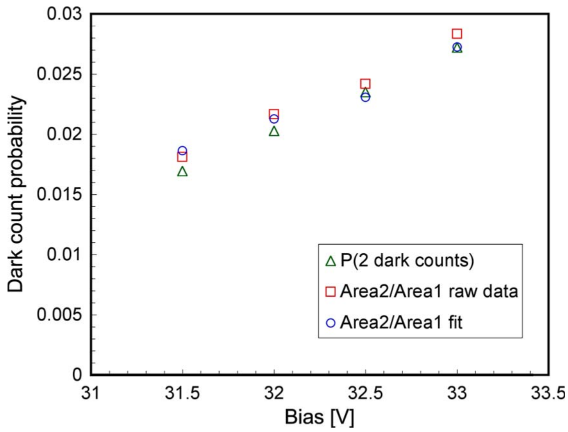

Fig. 13. Probability of noise counts versus bias voltage, evaluated by means of the following three methods: (circles) two-Gaussian fit to the plot of Fig. 12; (squares) direct sum of the counts under the peaks of the same plot; and (triangles) calculation of the probability of two noise counts within the gate duration, based on the results of Figs. 9 and 11.

V. Discussion

The sensor under study indeed showed a rather consistent noise rate, and this is a known limitation of this family of devices. Nonetheless, in spite of the 300–500-kHz noise pulses we measured, the device can be fruitfully exploited for the detection of very weak light pulses down to single photons. Certainly, when dealing with single photons, one should take the mixing with fake signals coming from dark noise into account; however, this can be easily overcome in the cases when an external trigger is available.

Our measurements showed that once the temperature is fixed, the noise behavior, although exponential, is reproducible and obeys simple mathematical laws. This makes the straightforward corrections due to dead-time and random noise pulse contamination possible.

For all the applications where a threshold at 1.5 photons can be employed, i.e., giving up to the detection of one-photon signals, the resulting cleanup is considerable as the noise decreases by about a factor 100–200 (Fig. 7). If one can afford a still higher threshold, for example, 2.5 or 3.5 photons, the noise can be even reduced to below 1 Hz. This is not true for devices with a relevant crosstalk noise; by looking, for instance, at the dark rate versus threshold plots in [9] and [13], one immediately realizes that the noise decreases by less than a factor of ten when increasing the threshold by one photon. The noise probability shown in Fig. 13 computed via charge measurement includes the crosstalk contribution, whereas the one computed by means of the exponential fit does not. Therefore, the small difference between the data points proves that the crosstalk is negligible, on the order of 0.2%.

VI. Conclusion

We have characterized a novel 100-channel SiPM, coming from an improvement of our previous SPAD technology. In particular, in this paper, we have shown a detailed characterization of its random and correlated noise features. The result is a working device with outstanding features in terms of single-photon resolution, timing, PDE, and noise, as will be also shown in the second part. The dedicated data-analysis procedure we developed and established allows for the extraction, at once, of the relevant parameters for the forthcoming generations of SiPM sensors.

The tests we performed and the features we measured as a function of the bias voltage and of the incident photon flux qualify this device as a very promising one, likely already suitable for physical measurement applications in the field.

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