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Silicon Photomultipliers: Dark Current and its Statistical Spread

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Abstract: Aim of this paper is to investigate on a statistical basis at the wafer level the relationship existing among the dark currents of the single pixel compared to the whole Silicon Photomultiplier array. This is the first time to our knowledge that such a comparison is made, crucial to pass this new technology to the semiconductor manufacturing standards. In particular, emission microscopy measurements and current measurements allowed us to conclude that optical trenches strongly improve the device performances. *Copyright © 2012 IFSA.*

Keywords: Silicon photomultipliers, Dark current, Wafer level.

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1. Introduction

Silicon-based single photon avalanche detectors [1-11] have been widely investigated since their appearance thanks to their interesting features: reduced dimensions, low weight, low fabrication costs, insensitivity to magnetic fields, and low operation voltage. Starting from single diode devices, progress in the field has driven the microelectronic industry to go towards designing and fabricating arrays of such devices, that is, avalanche diodes with an integrated quenching resistor connected in parallel by a metal grid and operating in Geiger mode, referred to as Si PhotoMultipliers (SiPMs), to cover areas up to ≈10 mm^2 per device (Fig. 1 *(a)* and *(b)*). The principle of operation of each single avalanche detector consists in a p-n junction biased above the breakdown voltage (BV). Thanks to the high quality substrate and fabrication technology (low defect concentration), it can remain quiescent above the BV until a photon is absorbed in the depletion volume. Once the photon is absorbed, the generated electron-hole (e-h) pair triggers a self-sustaining avalanche breakdown. The avalanche is switched off through an opportunely designed quenching resistor that reduces the voltage below breakdown as soon as the current flows through the diode.

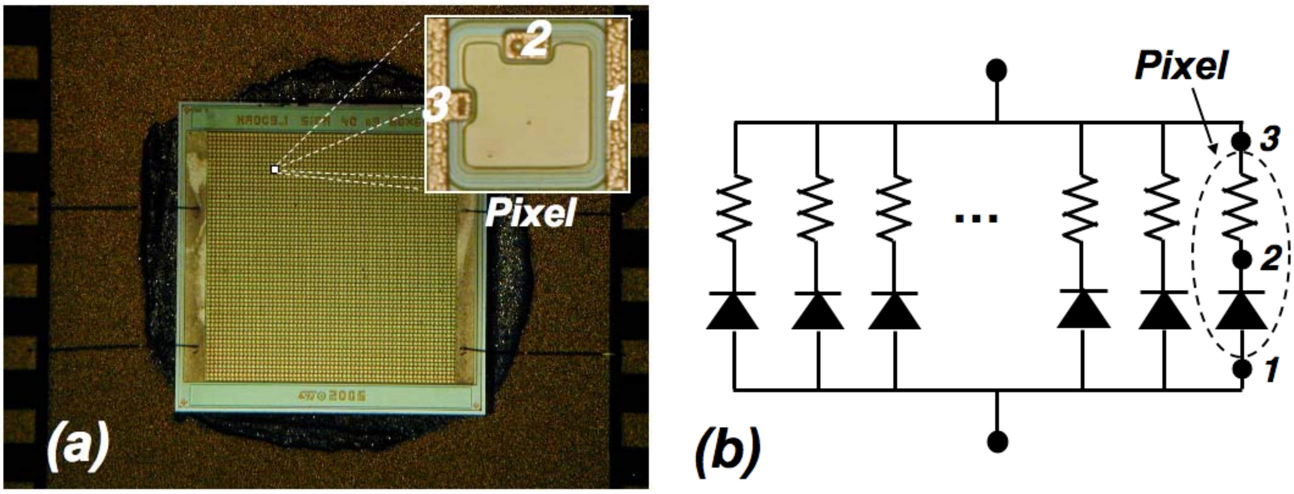

Fig. 1. (a) Microphotograph of a 64×64 pixels SiPM with 6.5 mm^2 active area produced by STMicroelectronics. The pixel, shown in the insect, has an active area of 40 μm × 40 μm. (b) Schematic circuit diagram of a SiPM. The pixel, enclosed by the dashed line, is composed of an APD and a quenching resistor. Note that node 1, 2 and 3 are the same in Fig. (a) and (b).

Each pixel of a SiPM works independently and produces the same output current pulse when fired by a photon. If multiple photons hit the SiPM area at the same time within the pixel time jitter, the SiPM output pulse is in the linear regime the parallel sum of the currents produced by each single pixel and then proportional to the number of pixels hit by a photon. In this way the single photon avalanche diode, with its digital response independent on the number of impinging photons when they are in coincidence, is transformed into an analog device able to quantify the number of photons arriving at the same time from a low intensity light source, though maintaining the photon counting ability.

Such ideal behavior is modified by the occurrence of phenomena leading to dark current in each pixel, generally attributed to generation/recombination effects from Shockley-Read-Hall (SRH) defects in the depletion layer sometimes assisted by the high electric field [12], diffusion of carriers from the quasi-neutral boundaries of the p-n junction, and afterpulsing effects [13]. In the whole SiPM detector the cross-talk between pixels can increase considerably the dark current, limiting the device operation capabilities [14]. The cross-talk is a noise contribution common in all pixelated devices. A current pulse produced by a pixel, due to a photon detection event or to a primary dark noise event, can trigger in one or more adjacent pixels a parasitic avalanche breakdown. The corresponding output current of the SiPM is then proportional to the number of involved pixels in the correlated cross-talk phenomena. This noise contribution is detrimental in all the applications where the single photon resolution is required. In order to reduce the crosstalk deep trenches can be fabricated around each pixel, though they imply a noticeable complication in the fabrication technology.

Aim of this paper is to investigate on a statistical basis at the wafer level the relationship existing among the dark currents of the single pixel compared to the whole SiPM array. This is the first time to our knowledge that such a comparison is made, crucial to pass this new technology to the semiconductor manufacturing standards.

2. Experimental

Single pixels and arrays of 64×64 pixels were fabricated in standard silicon planar technology starting from a Float Zone (FZ) low doped n-type substrate with a resistivity of ~ $4\cdot 10^3$ Ω·cm. A 2 μm p+ epitaxial layer doped with $9\cdot 10^{16}$ cm^{-3} Boron atoms is grown on the substrate. This highly doped layer forms a low resistance path for carriers moving from the active region to the anode contact and blocks the diffusion of carriers from the n substrate to the active volume of the p-n junction.

A 5 μm p epitaxial layer with a Boron concentration of ~10^{15} cm^{-3} is then grown on the p+ layer. Before the definition of the active region, p++ sinkers are created by a high boron implantation in order to reduce the anode contact resistance and provide a low resistance path to the avalanche current. An n-type guard ring surrounding the active volume is formed by arsenic implantation in order to prevent lateral breakdown. An enrichment region is obtained through B implantation, to define both the device active area and the BV (~ 28 V). The thin cathode is an n++ thin polysilicon layer doped *in-situ* with arsenic. A Rapid Thermal Anneal process allows the diffusion of the arsenic atoms in the p+ layer forming a shallow arsenic profile of ~ 0.15 μm [15] depth. The quenching resistor is integrated over the cathode of the cell itself and fabricated using low-doped polysilicon [16]. Thin optical trenches, filled with oxide and metal, surround the pixel active area in order to reduce electro-optical coupling effects (crosstalk) between adjacent pixels. A double-layer made of SiO_2 and SiN_3 is deposited on the top of the active region to form an anti-reflection coating (ARC). Different oxide layers are finally deposited in order to passivate the surface and the metal contacts are created by sputtering deposition of various metals. A schematic cross-section of the final structure of the single cell is shown in Fig. 2.

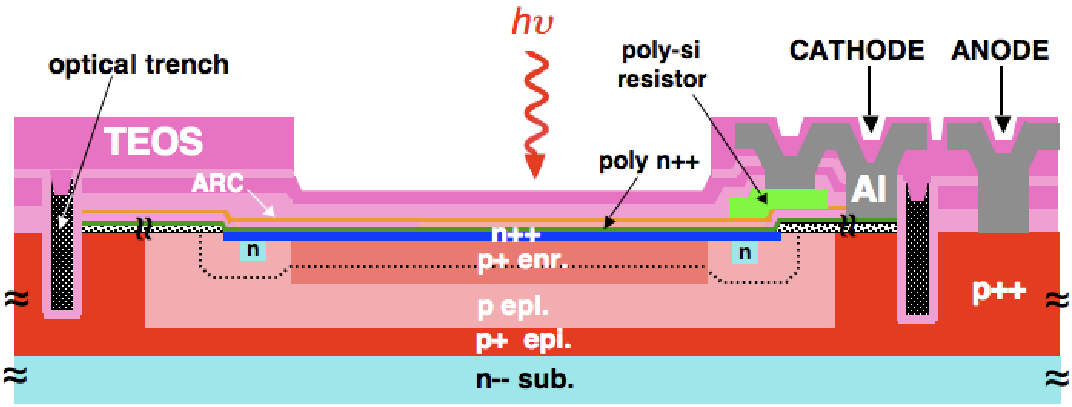

Fig. 2. Schematic cross section of the SiPM single pixel, showing the central active area with the diffused cathode (indicated as "n++"), the enriched anode ("p+"), the sub-anode ("p epi"), the anode contact region ("p+ epi"), the substrate ("n-- sub"), the ARC and the optical trenches.

Electrical characterization was performed at the wafer level using a Cascade Microtech Probe Station *11000*. The prober was shielded from visible radiation by means of a thick plastic cover to provide the required dark condition. The samples were cooled using a Temptronic *TPO 3200A* ThermoChuck that can provide a stabilized temperature between -60 °C and 200 °C. Current to voltage measurements were acquired using an *HP 4156B* precision semiconductor parameter analyzer using an integration time of 1 s, sufficient to correctly measure the current even at low temperature.

Emission microscopy (Em.Mi) measurements were carried out at 25 °C using an over-voltage (i.e. voltages above the junction breakdown voltage, ΔV) of 3 V.

Fig. 3 shows the 2D simulation of the electric field profile of a pixel performed at a bias polarization of -30 V. The 2D simulation has been performed using the Silvaco TCAD suite [17]. The electric field at the lateral border is well below its maximum value for junction breakdown and it is negligible with respect to the maximum value in the active region, in which, on the contrary, the field is above the critical field for avalanche breakdown.

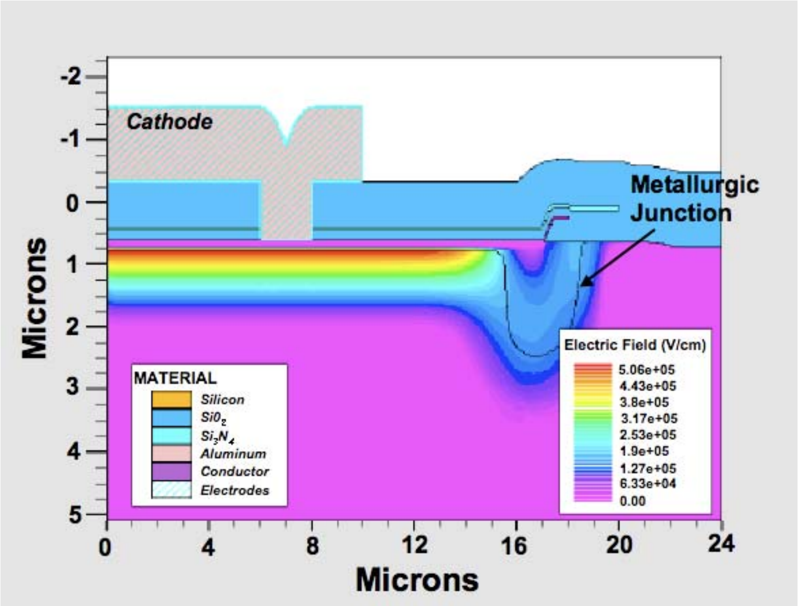

Fig. 3. 2D TCAD simulation of the electric profile performed at a bias polarization of -30 V in the structure sketched in Fig. 2.

3. Results and Discussion

In Fig. 4 it is shown typical dark current-voltage (I-V) characteristics of a single pixel in reverse polarization at 25 °C. The BV is -28.0 V in agreement with TCAD simulation. The I-V presents three distinct regions. The first, marked in green, extends from 0 V up to BV. The leakage current in this region is of the order of ~ 10 fA at 25 °C, close to the instrument sensitivity, and it has a linear behavior with respect to voltage. The second region, depicted in red, ranges from BV to about -34 V, i.e. from 0 to 20 % of the OV. The IV in this region has an abrupt increase with respect to the voltage and follows a cubic law as a function of the OV. Finally, in the third region, for voltage above -35 V in absolute value, depicted in blue, the current deviates from the cubic behavior and increases steeply with the voltage.

The second region is the operation voltage range for the single photon detection application. The pixel dark current in that region of interest is, as experimentally verified [18], given by:

$$I_D = q * G * DC = q * G * \left(\frac{N_{Def}}{\tau} + \frac{A_{Pixel}}{\tau_i} \right), \tag{1}$$

where q is the elementary charge, G the gain, *i.e.*, the total number of carriers generated in a single avalanche, from the avalanche buildup to the avalanche quenching and pixel recharge, DC is the dark count rate i.e. the number of avalanches per second in dark condition, given by [18]:

$$DC = \left(\frac{N_{Def}}{\tau} + \frac{A_{Pixel}}{\tau_i} \right), \tag{2}$$

where N_{Def} is the number of carrier generating defects per pixel in the active volume, τ the average time for carrier generation event per defect, A_{Pixel} the single pixel active area, τ_i the average time per unit area for the intrinsic carrier generation due to diffusion from the quasi neutral regions to the active volume.

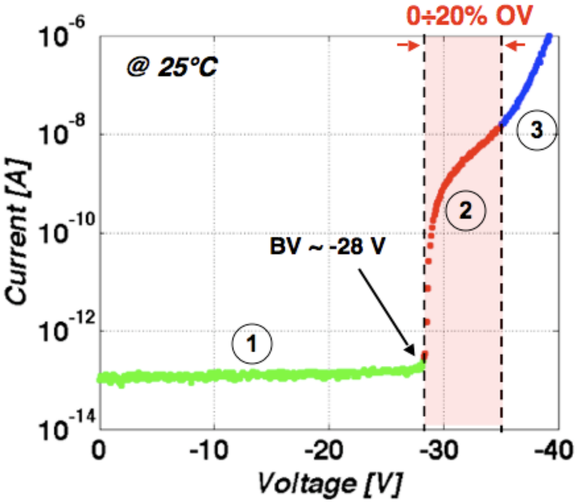

Fig. 4. Reverse current-voltage characteristic of a single pixel at 25 °C. Three different regions are shown.

Depending on the voltage dependence of both the gain and the dark count rate, the I-V characteristics show a well defined shape. In our devices it was found that the gain has a parabolic dependence [19] on the bias while the DC is a linear function [18]. Therefore, the product of these two terms explains the cubic dependence of the current with respect to the voltage.

At bias voltages higher than -35 V in absolute value the current increases more rapidly than a cubic law. This is mainly due to the increase of the afterpulsing effect and the inefficiency of the quenching mechanism.

The temperature dependence of the dark current gives useful insight on the mechanisms leading to the dark counts, indicating their origin, i.e. whether due to diffusion of minority carriers or to generation processes from SHR centers. Fig. 5 shows a typical example of an Arrhenius plots of the dark current at a constant $OV = 4$ V in a single pixel. The activation energy (E_a) is close to the silicon energy band gap (E_G = 1.12eV) when the reverse current is dominated by the diffusion of minority carriers and close to half of the silicon gap ($E_G/2$ = 0.56 eV) when dominated by mid-gap defects leading to SHR generation. The activation energy for temperatures above 50 °C is exactly 1.12 eV, evidencing that the diffusion of minority carriers is the dominant process at higher temperatures. At lower temperatures the activation energy of 0.59 eV clearly evidences that the generation from mid-gap SHR centers is the dominant dark count mechanism.

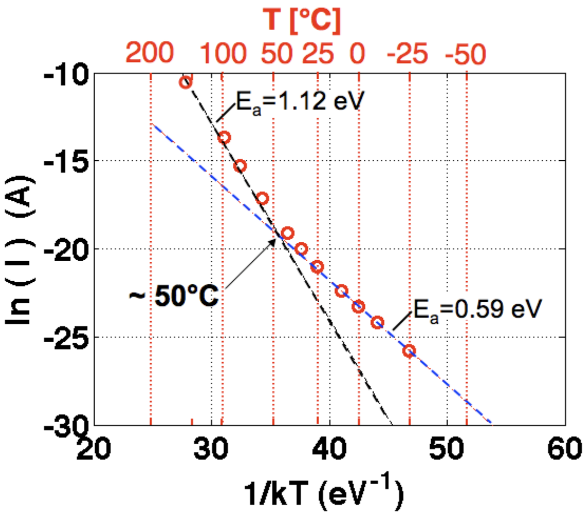

Fig. 5. Arrhenius plot of the dark current of a pixel at a fixed +4 *OV*. Black dashed line is the fit of the experimental data for temperature higher than 50 °C. Red dotted line is the fit of the experimental data for temperature lower than 50 °C.

In the whole SiPM detector, one of the major issues to solve is the minimization of the cross-talk effect among close pixels. An improper isolation scheme results in an avalanche correlation effect which triggers avalanches in close pixels (Fig. 6(a)). The avalanches in close pixels are likely triggered either by photons or by minority carriers produced by the avalanche of a primary pixel which migrates to close pixels causing new avalanches. The use of a proper electro/optical isolation trench scheme dramatically improves the situation (Fig. 6(b)), rendering negligible the cross-talk effect among neighbor pixels, and strongly reducing the dark current (from 300 to 10 μA).

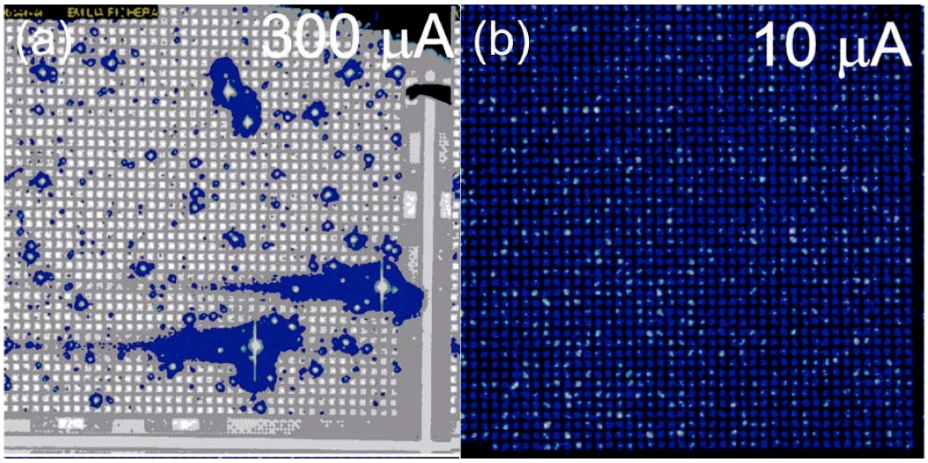

Fig. 6. Emission Microscopy measurements on SiPM arrays (a) without, and (b) with optical trenches.

The relationship among the dark currents in single pixels and in complete SiPM arrays is investigated in Fig. 7. We find that the I_D of the overall SiPM devices is simply the sum of the currents of single pixels as above modeled, with no contribution of extrinsic defects providing high leakage paths. In particular Fig. 6 shows frequency histograms comparing the dark currents measured at room temperature of single pixels and SiPM arrays for a total of 952 devices at over-voltages (*i.e.*, voltages above the junction breakdown voltage) of 2, 3, and 4 V. The SiPM device contains 4096 pixel, so the respective currents of SiPM to single pixel should stay in ratio of about 4,000, as actually found.

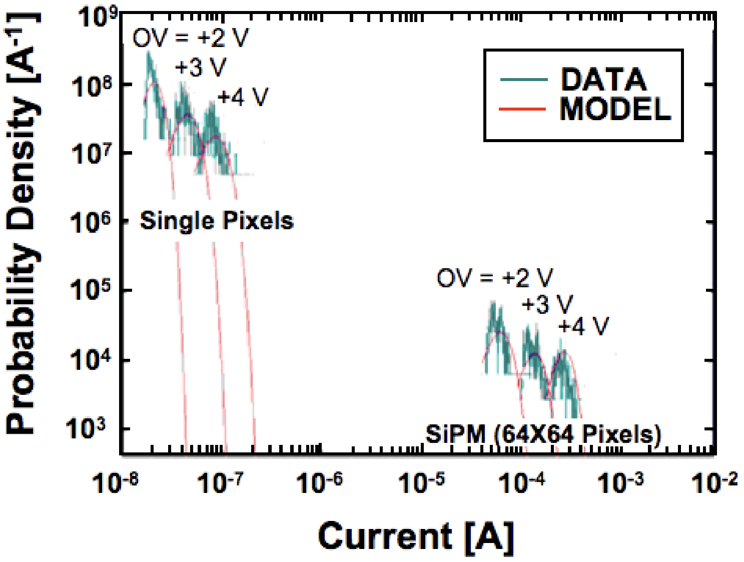

Fig. 7. Probability density as a function of the output current at over-voltages of 2 V, 3 V and 4 V, for both single pixels and arrays (having 4096 cells). The solid lines are the model results.

To model I_D in the present devices, we note that at room temperature the term N_{Def}/τ dominates, so the I_D statistics should essentially coicide with the N_{Def} statistics. The prevalence of the N_{Def}/τ term has been demonstrated through the temperature dependence of the leakage current, as reported in Fig. 5. For the N_{Def} statistics we assume the Poisson statistics so we find that the probability dP of having a dark count between I_D and I_D+dI_D is:

$$\frac{dP}{dI_D} = N * \exp\left[\frac{m_{I_D}}{\sigma^2_{I_D}}\left(I_D * \log(m_{I_D}/I_D) + (I_D - m_{I_D})\right)\right] \tag{3}$$

where N is normalization constant, m_{I_D} is the statistical average of the dark current and $\sigma^2_{I_D}$ is the variance. In the case of the SiPM arrays the same expression holds. Fig. 7 reports also the model curves, which show a good match with the experimental data. The model predicts that the combination of statistical parameters $\sigma^2_{I_D}/m_{I_D}$ should be equal to $q/\tau * G$ or $4096 * q/\tau * G$, for the single pixel and the SiPM array, respectively. Fig. 8 reports the experimental values of $\sigma^2_{I_D}/m_{I_D}$ as a function of the device overvoltage. As the overvoltage increases, $\sigma^2_{I_D}/m_{I_D}$ grows, due to the G increment. Moreover the ratio of $\sigma^2_{I_D}/m_{I_D}$ between SiPM and single pixel results of the order of 4,000 (Fig. 8), as predicted by the model. Further developments are ongoing. In particular we would like to mention that an improved version of our SiPM technology shows a further reduced dark current leakage. This is attributed to an improved minority carrier lifetime (larger τ_i in Eq. (2)), obtained through a better device architecture [20].

4. Conclusions

In this paper we report on the relationship among the dark currents of the single pixels compared to a complete Silicon Photomultiplier arrays. A good understanding of dark current in both cases has been reached. The experimental data, emission microscopy and dark current measurements, show that optical trenches strongly improve the device performances in term of reduction of the dark current.

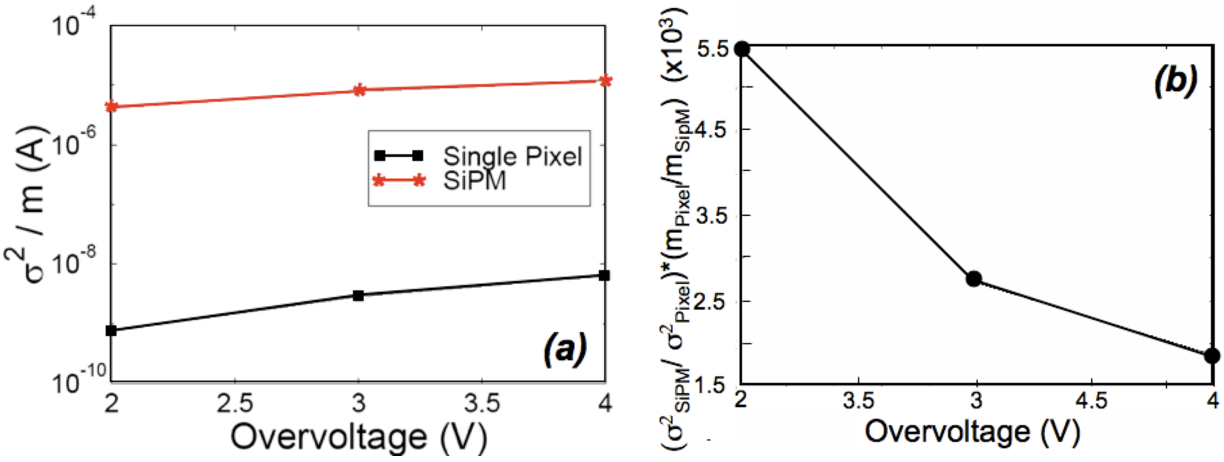

Fig. 8. (a) Experimental values of the variance divided by average device current as a function of the device over-voltage for the single pixel (in blue) and the SiPM (in red); (b) Experimental values of the ratio of the variance divided by the average device current between SiPMs and single pixels as a function of the over-voltage. The model, in good agreement with the experimental results, predicts that the ratio should be equal to the number of pixels in the SiPM device, equal to 4,096.

The dark current below 40 °C, as demonstrated by the Arrhenius plot for the single pixel, is dominated by SRH defects, while it is ideal at higher temperatures. SRH generation-recombination and diffusion models, coupled with Poisson Statistics catch quite well the behavior of dark currents in pixels, arrays, and statistical distribution. Further developments based on better device architecture aimed to a further reduction of the dark current are ongoing.

Acknowledgements

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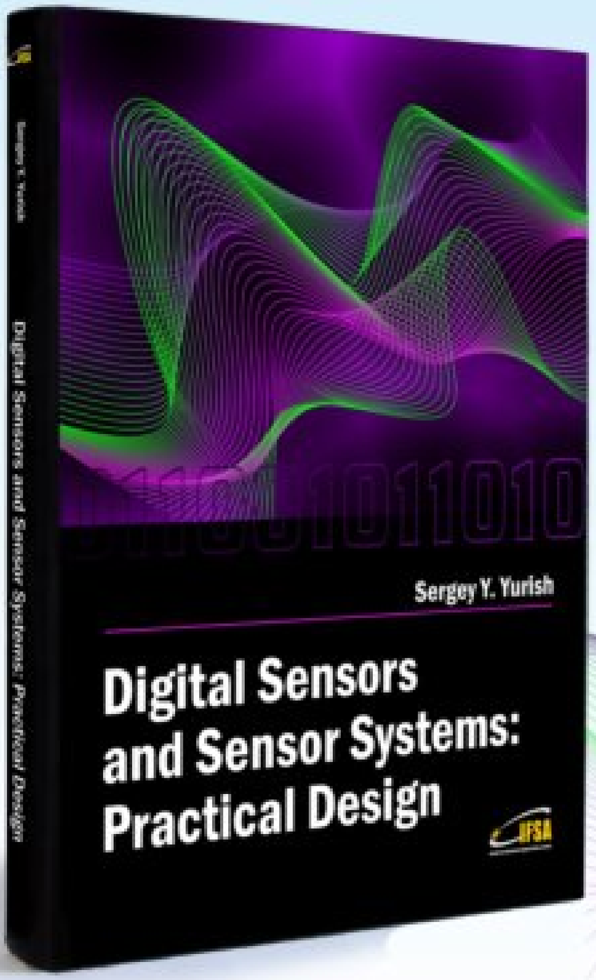

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