Development of large-area silicon photomultiplier detectors for PET applications at FBK
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Abstract
This paper reports on the development of large-area silicon photomultiplier (SiPM) detectors specifically designed for positron emission tomography (PET) instruments. The sensors under study are monolithic arrays of two different types: a 2 × 2 array of ~4 × 4 mm² elements and an 8 × 8 array of 1.5 × 1.5 mm² pixels. These devices are characterized at wafer level by means of an automatic test procedure, consisting of current–voltage curves in forward and reverse bias. The tests allowed selection of functioning devices and evaluation of the uniformity of basic parameters. Results of the electrical characterization are reported showing that acceptable values of yield together with rather uniform distribution of parameters have been obtained. Reliability of produced SiPMs has been proved by long-term accelerated stress tests.

1. Introduction

The silicon photomultiplier (SiPM) is obtaining a growing attention as an alternative to the traditional photomultiplier tube in the detection of low photon fluxes, thanks to a number of advantages, such as compactness, ruggedness, low operational voltage and insensitivity to magnetic fields [1]. SiPM could be successfully used in applications where efficient and fast detection of scintillation light is required, for example, in the fields of nuclear medicine and high-energy physics. Its use could be of particular interest when weight, dimensions, power consumption and presence of magnetic fields are a constraint.

This device could give important advancements in the field of positron emission tomography (PET) instrumentation since its small size enables a high sensor packing fraction, improving the obtainable resolution and efficiency [2]. Its time response characteristics are also suitable for time of flight (TOF) PET, which allows a significant improvement in PET image quality [3], while the insensitivity to magnetic fields makes it possible the combination in a unique instrument of the complementary capabilities of PET and magnetic resonance (MR) techniques [4]. Finally, SiPM devices offer the unique opportunity to build a combined PET/MR scanner with TOF capabilities.

FBK has been involved in the development of SiPM devices since 2005 in collaboration with the Italian National Institute for Nuclear Physics (INFN) [5,6]. A thorough characterization of the first 1 × 1 mm² SiPM prototypes in dark conditions is reported in [6], while electro-optical properties, timing performances and photodetection capabilities of scintillation light are described in [7–9]. In 2007, a new production of SiPMs with increased geometric fill factor was manufactured at FBK. New devices featured various micro-cell sizes ranging from 40 × 40 to 100 × 100 μm² and application-oriented geometries: among them single SiPM devices with dimensions up to 4 × 4 mm², linear SiPM arrays and matrices [10]. Given the encouraging results obtained with this production, in 2008 FBK started developing large-area SiPM matrices to be used in PET applications with the aim of improving the spatial resolution. In fact, arranging the SiPM devices in compact monolithic arrays allows for both a reduction in the dead area between the pixels as well as an easier and more reliable system design, which typically is rather complex in a PET instrument since it includes scintillator crystals and readout electronics.

This paper reports on the FBK experience in fabrication and testing of large-area monolithic arrays specifically designed for equipping PET scanners.

2. Sensor description

Subject of this paper are two different SiPM arrays for PET applications. The characteristics of the two sensor types are described below together with the main constraints put by the corresponding applications. The devices are being developed in the framework of two research programs aimed at building new PET instruments.

The first project, named HYPERImage, is funded by the European Commission through the 7th Framework Program [11]. Its main goal is the development of a new system for simultaneous whole-body PET/MR imaging for humans with high...
time resolution. The construction of a preclinical system for small animals is also foreseen as an intermediate step. To this aim, a compact modular PET detector has been conceived consisting of a $3.3 \times 3.3 \text{ cm}^2$ PCB stack including all the detection chains, from $\gamma$-photon detection to electric signal digitization [12]. SiPM detectors give the unique opportunity for sensing the scintillation light, given the presence of magnetic fields and the fast timing required by the applications. To this purpose, specific $2 \times 2$ monolithic arrays have been designed. Each SiPM has a dimension of about $4 \times 4 \text{ mm}^2$ and 3080 cells. Each PCB stack will be equipped with 16 of these SiPM arrays. The overall size of the array is $7.9 \times 8.1 \text{ mm}^2$. The geometric coverage (defined as the ratio between the effective area of the four SiPMs and that of the silicon die) obtained in this way is about 85%. This kind of device will be referred to in the following as HI detector. A picture of an array is shown in Fig. 1.

The second project (DASiPM2) is funded by the 5th INFN commission and aims at “development and application of SiPM to medical, space and high-energy physics” [13]. One of its objectives is the development of SiPMs to be used in a PET tomograph for small animals proposed by Pisa University [14]. It is based on detector heads consisting of a stack of three layers of continuous scintillator crystal slabs, each one conveniently coupled to compact SiPM photodetectors. Since the dimension of each slab is about $4 \times 4 \text{ cm}^2$, the use of large-area monolithic arrays will greatly simplify the assembly and improve both spatial resolution and sensitivity. Preliminary work has already been done in FBK by producing relatively small matrices of $2 \times 2$ [15] and $4 \times 4$ [16] pixels with good performances. The present work refers to a new SiPM array devoted to this application consisting of an $8 \times 8$ matrix with elements having $1.5 \times 1.5 \text{ mm}^2$ pitch and $50 \times 50 \mu\text{m}^2$ cell size. The overall dimension of the silicon die is $1.3 \times 1.3 \text{ cm}^2$ and the geometric coverage is between 67% and 78%, depending on the layout. This kind of devices will be referred to in the following as D2 detectors. A picture of an array having all bonding pads on a single edge is shown in Fig. 2.

Fabrication of both HI and D2 device types has been accomplished in the FBK microfabrication laboratory using p-type epitaxial silicon wafers with 100 mm diameter. The adopted technology is based on the conventional structure described in [5]. The number of arrays included in each wafer is 56 for HI devices, while it is equal to 16 for D2 detectors.

3. On-wafer characterization

Fabricated devices are characterized at wafer level by means of an automatic test procedure, consisting of current–voltage curves in forward and reverse bias. All SiPMs on the wafer are measured, both array pixels and single devices. In fact, a number of reference $1 \times 1 \text{ mm}^2$ SiPMs are usually included in the wafer layout, together with some test devices. Measurements are performed at a temperature of about $30 \, ^\circ\text{C}$ on an automatic probe station placed in the dark. The temperature is neither stabilized nor monitored during the measurements, but temperature variations have been estimated to be less than $3 \, ^\circ\text{C}$.

From the forward bias curves, measured up to $1.2 \, \text{V}$, the equivalent total resistance of each SiPM is evaluated fitting the linear part of the plot. The average quenching resistor $R_q$ is then calculated multiplying this value by the number of micro-cells. Reverse bias curves are measured up to a few volts above the breakdown voltage $V_{\text{bd}}$, the overvoltage ranging typically between 4 and 6 V. A voltage step of 1 V is used up to about 5 V below the $V_{\text{bd}}$, then it is reduced to 0.1 V for the remaining part of the sweep. An off-line algorithm has been developed to extract the $V_{\text{bd}}$ from the acquired curves. It identifies $V_{\text{bd}}$ as the maximum in the second derivative of the log($I$)-$V$ curves.

These tests allow for evaluation of characteristic SiPM parameters such as $V_{\text{bd}}$, $R_q$ and dark current values, as well as for the selection of functioning devices.

3.1. Breakdown voltage

As a first example, Fig. 3 shows the reverse $I$–$V$ curves measured on the four elements of an HI array. A $V_{\text{bd}}$ close to 30 V is obtained, which is the typical value for the FBK SiPMs. $V_{\text{bd}}$ differences among the four pixels can be estimated from the enlarged view reported in the inset and are within 0.3 V. Distributions of $V_{\text{bd}}$ values for three different wafers are reported in Fig. 4. The typical overall wafer dispersion ($\sigma$) is less than 1.5 V, while differences up to few volts are observed in the mean $V_{\text{bd}}$ value of different wafers. An important figure of merit is the $V_{\text{bd}}$ variability among the four SiPM elements of the same array. To this aim, we calculated the deviation of the single SiPM $V_{\text{bd}}$ with respect to the mean $V_{\text{bd}}$ value in the same array (indicated as $\Delta V_{\text{bd}}$). The $\Delta V_{\text{bd}}$ distribution evaluated on the HI
production is shown in Fig. 5. For about 85% of the SiPMs, the $V_{bd}$ is included in $\pm 0.2$ V.

Fig. 6 shows the reverse $I$–$V$ curves between 28 and 33 V for the 64 elements of a D2 array. A $V_{bd}$ close to 30 V is obtained also with this kind of devices. From the graph, the $V_{bd}$ differences inside the matrix can be estimated to about 0.5 V. The $V_{bd}$ distribution for the 64 SiPM elements belonging to the same array, evaluated on six wafers of the D2 production, is summarized in Fig. 7. The $6\sigma$ dispersion is about 0.6 V, in agreement with the estimation based on Fig. 6. $V_{bd}$ distribution curves on the same six D2 wafers are reported in Fig. 8. In this case, the $6\sigma$ dispersion values range between 1 and 2.5 V. Differences among $V_{bd}$ mean values of different wafers can be as large as 2 V, as observed for the HI samples.

3.2. Quenching resistance

The spatial distribution of the quenching resistor value $R_q$, evaluated on an entire wafer of HI devices, is reported in Fig. 9, showing a rather good uniformity among all SiPMs. The typical
single-wafer 6σ dispersion is in the order of 10% for all the production. For most wafers, the obtained mean $R_q$ value is between 270 and 330 kΩ.

For devices of the D2 production, the measured $R_q$ values are higher due to the different micro-cell layout. The mean $R_q$ values obtained on different wafers range from 400 to 500 kΩ, while the typical single-wafer 6σ dispersion is around 13%.

3.3. Dark current

Dark current values at 3 V above $V_{bd}$ have been chosen as a characteristic figure to perform comparisons among HI devices. They depend on wafer and batch, with values ranging from 25 to 90 μA. Variability at wafer level is in the order of 20% (6σ) for most of the wafers, while for a few of them it reaches 40%.

For D2 production, the reference dark current values have been taken at 2 V above $V_{bd}$ and have been normalized by the number of micro-cells in order to allow direct comparison of SiPM arrays with different layouts. For the matrix of Fig. 6, current values at 2 V above $V_{bd}$ are about 1 μA, corresponding to about 1.2 nA/cell. The average dark current values measured on different wafers range from 0.8 to 2 nA/cell, with most of the wafers having values close to 1.5 nA/cell. The single-wafer 6σ dispersion is between 20% and 30%.

The dark current is related to the SiPM gain and to the thermal-induced dark count rate; thus, the observed variability depends on variations in these two parameters. The gain can be considered constant, being determined by the cell geometry (identical for all devices in each production) and by the epitaxial layer thickness. Therefore, the main source of variability should be ascribed to variations in the dark count rate. This is a reasonable assumption because the dark count rate could be influenced by few noisy micro-cells associated at the possible presence of localized defects in the wafers, with their number fluctuating in different devices and wafers. Experimental measurements on monolithic 4×4 SiPM matrices previously fabricated in FBK confirm that the dark count rate variability is larger than that of gain [17].

3.4. Production yield

The tests described above also allowed selection between functioning and defective devices. The second class includes devices with premature breakdown, high current values before and/or after breakdown and high and/or low forward currents.

The main defect influencing the yield of both productions was the presence of premature breakdown, whose effects on the yield varied from wafer to wafer. Most of the defective matrices had only one faulty SiPM with premature breakdown. The impact on the yield of the other failure modes was negligible.

Up to now, about 700 full functioning HI arrays have been produced, which will be employed in the small animal PET/MR system. On the wafers, where the premature breakdown problem was less pronounced, though remaining the main cause of failure, the obtained yield was about 75%. Concerning the D2 arrays, an yield greater than 65% was obtained on the best wafers, which increases to more than 90% if we consider the matrices with 1 non-working element (out of 64) as also functional.
The above-mentioned numbers are quite satisfactory considering that these are the first large-area SiPM productions at FBK. On the other hand, some effort must be put on the technology to further improve the yield.

4. Failure analysis

As pointed out in the previous section, the most common defect limiting the yield was a premature breakdown. We tried to study the origin of this defect.

A first analysis involved the shape of the $I-V$ curve above the breakdown. For functioning SiPM devices, the current above $V_{bd}$ is given by the product of the dark count rate and gain, which gives a parabolic shape with respect to the overvoltage [6]. Curve (a) in Fig. 10 is an example of an experimental $I-V$ for a good device with a superimposed fitting curve calculated using appropriate values for dark count rate and gain. A typical $I-V$ plot for SiPMs having premature breakdown is represented by curve (b) in Fig. 10, showing a premature breakdown voltage $V_{bd}$ at 13.5 V. In this case, the overvoltage behaviour is well fitted by a linear dependence, indicating a resistance limited operation, and the value of the resistor turned out to be the quenching resistance $R_q$ of that SiPM device. Therefore, the anomalous behaviour could be assigned to a current flowing through only one defective micro-cell. This behaviour was typical for devices with premature breakdown.

To get more insight on this point we acquired light emission images of defective SiPMs biased above $V_{bd}$ using an IR camera mounted on a microscope [18]. Emission images confirmed the presence of only one localized emission spot as shown in the picture reported in Fig. 11, where the emission image has been superimposed to a conventional optical image.

Additional dedicated tests have been planned, in particular, to understand if the defect is originating during the fabrication process or should be attributed to the starting silicon material.

5. Stability tests

Sample devices from FBK SiPM productions are routinely selected to perform stability test. To this aim, they are biased a few volts above $V_{bd}$ (typical overvoltages range from 3 to 6 V) while the dark current is monitored as a function of the time.

To check at a higher safety degree the stability of the devices under long-term operation, a packaged $3 \times 3$ mm$^2$ single SiPM from D2 production was subjected to a sequence of two accelerated stress tests. The first one was a stability test where the device was biased at 38 V for almost 6 days at 60 °C in the dark. The device was placed in a climatic chamber that assured temperature stability within 0.4 °C. In the second test, 6.5 days long, the device was kept in the same conditions (38 V bias, 60 °C temperature) under a light source that induced a current level a factor 10 higher than the dark value. During both tests the device current was monitored as a function of the time. The $V_{bd}$ of the SiPM under test was about 31 V at 25 °C and 33.8 V at 60 °C.

The current vs. time plot during the first test is reported in Fig. 12. The rather fast oscillations in the measured current reflect the resolution of the current meter (0.1 μA). The slow fluctuations with amplitude $\sim 1 \, \mu\text{A}$ and 24 h period indicate a dependence on ambient conditions. This was confirmed by daily fluctuations of the laboratory temperature that was measured starting by the third day and is also reported in Fig. 12. Fluctuations in device current and room temperature are very well correlated. Variations in room temperature are rather large and probably affect the measurement instruments. Residual possible intrinsic drift of the device dark current is completely hidden by this effect; therefore, it could be estimated well below 0.5%.

During the second test the light source was not stabilized, hence the device current could not be used to monitor the intrinsic device behaviour. The effects of the stress on the device characteristics have been evaluated by comparing $I-V$ curves measured in the dark at 25 °C and collected at different test times. In particular, $I-V$ curves up to 40 V (9 V above $V_{bd}$) have been taken: before all the stresses; in between the 2 tests; just after the second test; 2 days after the second test (while the device was left unbiased). The device current below $V_{bd}$ shows some variations after the 2 stresses, up to a factor 2 higher than the original value. However, this is a reversible phenomenon, probably due to surface effects, and in the last $I-V$ curve the current is lower than the original one. On the contrary, negligible effects have been observed on the dark current above $V_{bd}$.

6. Conclusion

In this paper we reported on the FBK experience in fabrication and testing of two different large-area monolithic arrays specifically designed for equipping PET instruments. The considered devices were respectively a $2 \times 2$ array of $\sim 4 \times 4$ mm$^2$ elements and an $8 \times 8$
array of $1.5 \times 1.5 \text{mm}^2$. Results of the electrical characterization performed at wafer level on the fabricated devices were reported, showing that an acceptable uniformity of basic parameters such as breakdown voltage, quenching resistance and dark current values were obtained. The tests allowed selection of full functioning matrices giving an estimation of attainable values of yield for large-area devices. Good yield values have been obtained on many wafers in both considered productions. On few wafers the yield was impacted by the presence of a relative large number of micro-cells with early breakdown. Work is ongoing to solve this issue. Long-term operation of single SiPM devices fabricated in the same production of the arrays has been demonstrated by means of accelerated stress tests at high temperature and high illumination levels.

Encouraging results have been obtained in the preliminary functional tests performed by the partners of the corresponding research projects. In the case of HI devices, prototype PET modules have been assembled and their overall functionality has been proved, including acquisition of $^{22}$Na spectra with a LYSO crystal coupled to the SiPM matrix [12]. Also an $8 \times 8$ D2 matrix has been assembled with a 64-channels readout chip and a continuous slab of LYSO crystal. Preliminary tests are under way with rather good results in terms of spectroscopic characteristics and spatial resolution.

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References