Solid state photodetectors for nuclear medical imaging applications

M. Mazzillo[(a)], P.G. Fallica[(a)], E. Ficarra[(c)] A. Messina[(a)], M.Romeo[(a)] R.Zafalon[(b)]
(a)STMicroelectronics, IMS- R&D Catania, Italy; (b)European R&D and Public Affairs, STMicroelectronics, Italy; (c)Politecnico di Torino, Italy

Abstract

One of the most important challenges facing the entire globe is the trend towards an aging population. By 2045, there will be more people over 60 years old than younger than 15, thus raising from 600mln to 2bln worldwide. This will raise the number of patients with age-specific, chronic and degenerative diseases (e.g. cardio-vascular, cancer, diabetes, Alzheimer's, Parkinson's). Minimally-invasive imaging technologies such as PET (Positron Emission Tomography) and MRI (Magnetic Resonance Imaging) play a vital role in detecting and tracking the evolution of the above mentioned illnesses and determining the strategy and the effectiveness of the prescribed therapies. So far the detection unit of PET equipment has been implemented using photomultipliers tubes (PMTs). A novel solid state photo-detector, the Silicon photomultiplier (SiPM), can replace the PMT, offering, among many other advantages, the possibility of PET/MRI combo equipment.

Keywords: Nuclear Medicine, Photomultiplier, central nervous system's diagnostics, PET, SiPM.

1. Introduction

Chronic and degenerative diseases are serious illnesses requiring some of the most expensive diagnosis/therapy procedures. In addition, these diseases are among those with the fastest growing impact on society.

•**Surging healthcare costs**: growing from 9% on 2008 of worldwide gross domestic product (GDP) to an expected 15% by 2015.

•**Healthcare professional staffing shortages**: due to higher demand for patient's care not met by recruitment and training of professional caregivers staff at all levels, from medical to paramedical.

•**Efficiency and effectiveness of healthcare's process**: need to improve quickly to cope with demand given the higher expectations of the final service patients.

Among the semiconductor industry, STMicroelectronics (hereafter ST) has a strategic commitment in healthcare since the high rate of innovation in electro-optical micro-systems is a key strength of the Company that can bring immediate benefit to the medical applications. More specifically the focus on new diagnostic equipments will allow it to take advantage of all benefits offered from fully integrated silicon sensors (i.e. in terms of resolution performance, industrial cost, power consumption, higher reliability, lower maintenance, smaller and lighter equipments, lower healthcare costs and higher standard quality).

2. Positron Emission Tomography (PET)

PET is a nuclear medicine imaging technique which produces a three-dimensional image of functional processes in the body. To conduct the scan, a short-lived radioactive tracer isotope is injected into the living subject (usually into blood circulation). The tracer is chemically incorporated into a biologically active molecule. There is a waiting period while the active molecule becomes concentrated in tissues of interest; then the patient is placed in the imaging scanner. During the scan a record of tissue concentration is made as the tracer decays. As the radioisotope undergoes positron emission decay (positive beta decay), it emits a positron, an antiparticle of the electron with opposite charge. The emitted positron travels in tissue for a short distance (typically less than 1 mm), during which time it loses kinetic energy, until it decelerates to a point where it can interact with an electron. The encounter annihilates both electron and positron, producing a pair of annihilation (gamma) photons moving in approximately opposite directions. These are detected when they reach a scintillating crystal in the scanning device, creating a burst of light which is detected by a photo-sensor. The PET technique depends on simultaneous or coincident detection of the pair of photons moving in approximately opposite direction (named coincidences).

Images of tracer concentration in 3-dimensional or 4-dimensional space (the 4th dimension being time) within the body are then reconstructed by computer graphics. In the PET machine the core device is therefore the photo-detector: the overall PET system diagnostic's performance relies on photo-detector's feature [1].

3. Silicon PhotoMultiplier (SiPM)

SiPM is based on an array of special diodes (SPAD: Single Photon Avalanche Diodes) that are biased over the breakdown and individually operates as a photon counters (see Figure 1). When a diode detects a photon, an avalanche current is generated. The current flow in the diode is switched off by an integrated large value resistor; as a consequence, the diode is reset, ready to detect another photon. Since in a SiPM all the outputs of the pixels are connected together, the device behaves as a proportional device for photon fluxes [2]. The SiPM has many advantages with respect to standard vacuum Photomultiplier Tubes (PMTs) typically used as photo-detectors used in PET machines. SiPMs are in fact extremely compact, robust and easy to operate due to the low operating voltage (30-40 V). Moreover the solid-state detector approach has the typical advantages of the planar process integration; therefore SiPMs can be manufactured at low cost and reproducibility. Fast timing response, very good single-photon detection capability, high detection efficiency in all the visible and near infrared wavelength ranges, excellent temperature and voltage stability and the insensitivity to magnetic fields (needful in innovative devices such as integrated PET/MRI scans) are other favourable SiPM's characteristics. Thanks to all these properties, SiPM technology is currently promising to fulfil the requirements of PET readout unit and find widespread use in nuclear medical imaging [1]-[2]. In this context, we have developed a dedicated technology which is not a derivative of standard CMOS with the aim to realize a device with a high signal to noise ratio in a wide range of operative conditions (bias, temperature and detection wavelength). Dedicated process and device simulation tools (SILVACO®) were used

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for this purpose. Moreover the fabrication process has been designed in order to minimize the junction leakage currents and dark count rate and increase as much as possible SiPM's photon detection efficiency in the emission wavelength range of scintillating crystals.

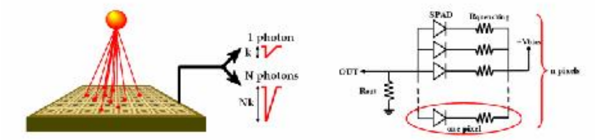

Fig. 1 <u>Left</u> - Scheme of principle of a silicon photomultiplier (SiPM) based on an array of SPAD sensors with passive common readout; <u>Right</u> - Electrical scheme of the SiPM, biasing circuit and output signal extraction.

The STMicroelectronics SiPM structure is fabricated in R&D Catania clean room facilities on silicon epitaxial p-type wafers and formed from planar N+-P microcells. The quenching resistor, made from low-doped polysilicon, is integrated inside the cell. Thin optical trenches filled with oxide and metal surround the microcell active area in order to reduce electro-optical coupling effects (crosstalk) between adjacent pixels. A suitable double-layer antireflective coating is deposited on the surface of the device to enhance its spectral response in the blue and near ultraviolet wavelength ranges. Moreover the exposed silicon surface area was carefully maintained clean during all of the processes to the end, in some case protected by sacrificial oxide layers, to avoid any contamination. Further details about the SiPM manufacturing method are reported in [2].

An electric model has been developed using SPICE simulator in order to predict the electrical behavior of the device in different bias and illumination conditions.

In Fig. 2 we report an optical microscopy image of a large area SiPM. The device has a square geometry with a total area 3.5x3.5 mm2, 3600 microcells and a geometrical fill factor of 45%. Each microcell in the array has a square geometry with an active area 40x40 µm2 and pitch 58 µm. The devices are mounted in an appropriate SMD package with a suitable optical transparent resin.

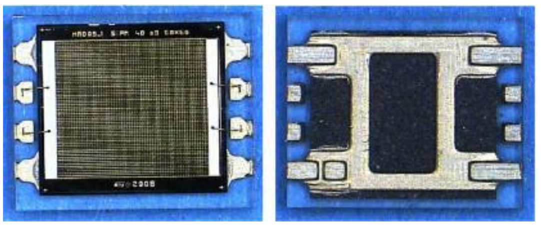

Fig. 2 – Optical microscopy image of a large area SiPM in a suitable SMD package in Top (left) and Bottom (right) view.

SiPM samples with different total area, number of microcells and packaged in TO cans are currently also available for their possible use in different applications.

In figure 3 a typical charge spectrum obtained on a large area SiPM illuminated by a fast pulsed laser (40 ps FWHM pulsewidth) at 405 nm wavelength is reported. The charge from 1 to n microcells, where n is the number of peaks in the spectrum was measured by using an appropriate equipment. About 30 peaks, corresponding to 1–30 activated microcells (i.e. detected photons), can be clearly separated in the spectrum, confirming the excellent photon counting properties of the SiPM in low intensity illumination regime [3].

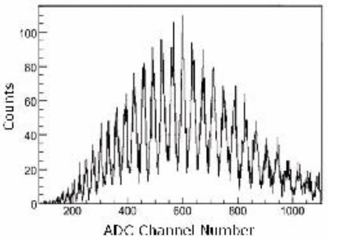

Fig. 3 – Typical charge spectrum obtained in low intensity illumination regime on a large area SiPM. Each peak corresponds to an activated microcell (i.e. a detected photon) [3].

4. Image Processing and Technology Trends

The higher the number of detectors, the more accurate will be the spatial resolution of the whole PET system. Moreover, to increase the detection sensitivity the detector is requested to achieve a very tight time resolution. Such an aggressive timing resolution and high sensitiveness will allow to reduce random coincidences and to achieve a very accurate spatial resolution. Thus, given the properties of SiPM sensors, a large number of them will be integrated into a 2-D array, to enhance the PET spatial resolution with respect to the standard detection units. With continuing improvements in spatial resolution, small patient movements during PET imaging become a significant source of resolution degradation. This leads to investigate comprehensive formalisms for accurate motion-compensated reconstruction methods [4]. In particular, it is needed an effective method to incorporate presence of scattered and random coincidences in the context of motion. The overall reconstruction framework should take into consideration missing projection data which are not detected due to motion, and additionally, incorporates information from all detected events, including those which fall outside the field-of-view following motion correction [4].

5. Conclusions

In this paper we have presented the main characteristics of STMicroelectronics SiPM technology realized in R&D Catania clean room facilities. Silicon photomultipliers present several promising features for nuclear medical imaging applications, among them the insensitivity to magnetic fields, the compactness, excellent timing performances and single photon counting capability. The device is characterized by a low dark count rate, a good photon detection efficiency and very good photon counting properties for low as well moderate photon fluxes. All these characteristics seem really promising in view of the final use of these devices in PET where detectors with excellent performances in terms of very fast timing and energy resolution are required.

6. References

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