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Overview of Silicon Photomultiplier Applications

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Multicell Geiger-mode avalanche photodiodes, or silicon photomultipliers (SiPMs), have proven to be a sound alternative to other types of photodetectors in different fields and have advantages that can significantly overcome performances previously achieved, and enable new possibilities. SiPM development continues with the improvement of general properties, and the enhancement of determined characteristics to fulfil specific requirements for different applications. As the number of SiPM manufacturers rises, their properties improve and more possibilities for readout appear in the market, an increasing number of physics experiments tend to replace other type of photodetectors by SiPMs, or to employ them in innovative applications. SiPMs have been successfully applied or are being tested in numerous applications in high energy physics (in calorimeters for CALICE, in T2K or in Cherenkov detectors), in astroparticle physics (such as MAGIC or EUSO), and in medical imaging (for example in the combination of PET and MR imaging modalities or for time of flight PET).

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1. Introduction

Multicell Geiger-mode Avalanche photodiodes, commonly known as Silicon Photomultipliers (SiPMs), have experienced a fast development in the last ten years. This technology is now mature enough to be employed in numerous experiments, overcoming the performance of other types of photodetectors. At the same time SiPM research is still an active field, with new designs and developments ongoing.

The advantages of SiPMs are known. The compactness and design flexibility of solid state detectors makes them easily adaptable to different applications by tailoring their structure, size or microcell size to enhance the desired properties such as photon detection efficiency (PDE), already larger than most photomultiplier tubes (PMTs) and still increasing, or dynamic range. They also have a fast time response and they are insensitive to magnetic fields. Among their main disadvantages are sensitivity to temperature and bias voltage variations, a high dark count rate and a PDE that is still too low for some applications. Since the noise scales linearly with area, detectors tend to be small. Radiation damage, which results in increased dark count rates and afterpulse probability, can be a limitation for some applications, in particular those in which the detection of single or a low number of photons is required.

The number of commercial manufacturers has also increased significantly. These facts make that an always growing number of experiments and applications consider SiPMs as possible photodetectors, replacing the ones currently in use or making further advances possible in some fields.

This paper is a short overview of the main trends and recent advances. Far from being exhaustive, it provides a short description and status report of some example applications in high energy physics, astroparticle physics and medical imaging.

2. Calorimetry

Calorimetry for future particle physics experiments is one of the first applications using SiPMs at large scale. This is the case of the analog hadronic calorimeter (AHCAL) or the electromagnetic calorimeter developed by the CALICE collaboration for the International Linear Collider (ILC). SiPMs are also considered for the upgrade of current experiments, where they can improve the performance of detectors in use. One of the main advantages is the possibility of significantly increasing the detector granularity when coupled to scintillators with wavelength shifting (WLS) fibers. In addition, their insensitivity to magnetic fields allows their operation inside the magnets. Very large numbers of SiPMs are needed, and thus, a mass production with relatively similar characteristics at low cost should be achievable.

The calorimeters designed for the future linear collider detectors follow the particle flow approach, which combines information from trackers (charged particles) and calorimeters ECAL (photons and electrons) and HCAL (hadrons). Very high granularity is required to distinguish details of hadron showers, with a high integration level. The CALICE Hadronic Calorimeter for ILC is a pioneering detector development using SiPMs. A first prototype was initially assembled and tested employing $\sim$8000 SiPMs from MEPhI/PULSAR [1]. An upgraded version employs plastic scintillator tiles of $30 \times 30 \times 3$ mm size with WLS fibers mirrored on one side and read out with 1 mm^2 CPTA/Photonique SiPMs of 796 microcells on the other side, making a module of 36×36

tiles [2]. The SPIROC ASIC serves as front-end electronics. Tests have been carried out in a 2-6 GeV electron beam. The results show 95% minimum ionizing particle (MIP) detection efficiency in self trigger mode setting the threshold so that the ratio of the number of noise events and the number of MIP events is below 10^{-4}.

The CALICE Electromagnetic Tungsten-scintillator sampling calorimeter (ScECAL) is also employing MPPCs from Hamamatsu. In this case, absorber layers of 3.5 mm thick Tungsten are used, and three types of tiles have been tested in three half-detectors: two types of so-called megastrips (9 $\times$ 4.5 $\times$ 0.3 cm) with and without WLS fibers and scintillator strips (1.0 $\times$ 4.5 $\times$ 0.3 mm) with a 1 mm hole to place the WLS fiber fabricated with the extrusion method. The final design incorporates reflector foils to isolate strips optically. Results in test beams demonstrate the feasibility of this detector concept [3].

The high luminosity upgrade of the Large Hadron Collider (LHC) at CERN will require the upgrade of some of the detectors. In the case of the CMS Outer Hadron Calorimeter upgrade, SiPM-based detectors will replace the Hybrid Photodiodes (HPDs), which are susceptible to discharge at intermediate magnetic fields. Tests indicate that SiPM PDE is more than two times that of HPDs and the gain is a factor of 50 to 500 times larger. SiPMs also take advantage of being compact and not being affected by the magnetic field. In addition the bias voltage is 100 V compared to 10 kV for HPDs [4]. The full SiPM system will be installed during the LHC LS1 shutdown in 2013.

The Tokai-to-Kamioka (T2K) experiment is a long baseline neutrino oscillation experiment for ν_e appearance search. The experiment detectors are a near neutrino detector complex (ND280), placed at JPARC (Japan), and a far neutrino detector, Superkamiokande. The ND280 is located 280 m from the pion production target and it is composed of two detectors, the on-axis neutrino beam monitor (INGRID) and the off-axis detector, made, in turn, of several subdetectors. Both the on-axis detector and several calorimeters of the off-axis subdetectors are composed of scintillator bars of different sizes and configurations, read out by WLS fibers either with SiPMs on two sides or on one side and mirrored on the other side. SiPMs have been selected as photosensors based on their PDE matching the emission of the WLS fibers, their insensitivity to magnetic fields, and their compactness, given the space constraints. The SiPMs selected matching the experiment requirements are MPPCs from Hamamatsu of size 1.3 mm^2, 667 microcells with 50 $\mu\mathrm{m}^2$ microcell size, low cross talk (about 10%), PDE $\geq$25% for green light, dark rate of 0.3 MHz at the operating voltage and gain of about 7×10^5. This is the first large scale application of SiPMs in an experiment, with about 60000 units required [5].

3. Cherenkov detectors

Cherenkov detectors require the detection of low light level fluxes, on the order of single or few photons. Thus, high PDE, low dark rate and low cross-talk are essential. Specific developments are ongoing in this field for some experiments [6]. SiPMs are being tested for Cherenkov telescopes for astroparticle physics experiments, and considered in HEP experiments for RICH (Ring Imaging Cherenkov) detectors in the upgrade of the Belle spectrometer (KEKB e+e- collider), or ALICE (LHC) at CERN, and also in DIRC (Detector of Internally Reflected Cherenkov light) detectors for the PANDA experiment at the FAIR facility [7]. SiPMs are considered promising candidates for RICH counters based on direct detection of photons [8]. They are under study, among other options, as photodetectors in Focusing Aerogel Ring Imaging Cherenkov (FARICH) detectors for the upgrade of different experiments.

The upgrade of the Belle particle identification (PID) system will require a 4σ separation of kaons from pions up to a momentum of 4 GeV/c. A proximity focusing RICH with aerogel radiator would meet the limited space constraints. Other issues to consider are the presence of a magnetic field of 1.5 T and radiation damage. A test detector module has been mounted with 64 (8x8) MPPCs of 1 mm^2 size and 100 μm microcell size. Pyramidal light concentrators have been employed to increase the signal to noise ratio and the effective area of the sensor while maintaining the noise level. The module has been tested in a 120 GeV pion beam, profiting from the fast timing properties of SiPMs to apply time windows for event selection and noise reduction. The results show that 3.7 photons per ring were detected. Improvements in aerogel and light guide coupling could lead to the detection of up to 30 photons per ring, making the detector performance suitable for this application [9].

A FARICH detector, employing multi-layer silica aerogel as radiator, is also being tested as a possible upgrade for the ALICE high momentum PID system, which is expected to extend the momentum range of the charged particle ID up to 10 GeV/c for pion-kaon separation and to 14 GeV/c for kaon proton separation [10], and also for the Super Charm-Tau Factory project at BINP (Novosibirsk). A detector employing Winston-cone light collectors coupled to SiPMs (MRS APDs from CPTA) has been assembled and tested in a 6 GeV/c negative pion beam. A FARICH Cherenkov angle resolution of about 2.1 mrad sigma was obtained, taking into account the prototype geometrical efficiency. Digital SiPMs from Philips are also being tested for this application [11].

Within the Cherenkov telescopes for astroparticle applications, SiPMs are being tested both for ground based and space telescopes. Atmospheric Cherenkov telescopes are employed to study some of the most energetic galactic and extragalactic objects such as active galatic nuclei, supernova remnants or gamma-ray bursts. Very High Energy (VHE) gamma rays, in the range of tens of GeV to TeV, induce Extensive Air Showers (EAS) when entering the atmosphere and the secondary particles produce Cherenkov light that is detected by the telescopes. Large areas and fast photodetectors with high PDE in the UV and blue range are required. In this case no external trigger can be applied, and thus the reduction of dark rate is essential. In addition, these experiments suffer from high temperature variations which must be compensated. Research is ongoing for high PDE, large area, optical crosstalk and afterpulse suppression for MAGIC and CTA (Cherenkov Telescope Array) [6]. The first test of the use of SiPMs was carried out at the MAGIC telescope [12]. A small detector was developed consisting of an array of 2×2 MPPCs of 3 mm^2 size and 50 μm^2 microcell size from Hamamatsu. A two-stage light concentrator consisting of a light catcher of high reflective foil and a Plexiglas light concentrator was placed on top of each MPPC to enhance the effective area of each sensor. The detector was mounted on the entrance window of the MAGIC camera, in place of one of the PMTs. A small amplifier was situated close to the detector, and the MAGIC data acquisition (DAQ) system was employed as readout for the detection of air-shower Cherenkov light. The comparison with neighbour PMTs showed an increase in detection efficiency greater than 60% after scaling for the difference in detector areas.

The FACT (First G-APD Cherenkov Telescope) project evaluates the use of SiPMs in Imaging Atmospheric Cherenkov Telescopes (IACT). A first prototype made of 144, 3×3 mm^2 Hamamatsu MPPCs with 50 μm^2 microcell size was initially developed and tested. The Domino Ring Sampling (DRS2) chip was employed for readout [14]. A feedback system for temperature variation compensation was developed based on LED signals which modifies the bias voltage according to temperature changes. With this system, the signals were kept constant to within 0.5 %. The complete FACT camera is composed of 1440 SiPMs with light collecting cones. The improved version of the chip, DRS4, replaces the DRS2. The system is installed on a former HEGRA telescope, upgraded with refurbished mirrors, a new drive system, and a new DAQ system. The camera is functioning with reliable and stable operation under varying conditions, and commissioning is ongoing [15].

The JEM-EUSO (Extreme Universe Space Observatory on-board Japanese Experiment Module) project is based on the construction of a space borne fluorescence telescope to be installed at the International Space Station for the observation of extreme energy cosmic rays, pointing at the Earth to detect Cherenkov light from the atmosphere [13]. Low power consumption and low weight are essential in this case. A camera has been built employing 16 arrays of 16 MPPCs each, developed by Hamamatsu in a collaboration with Max Plank Institut für Physik for application in IACT experiments including MAGIC/MAGIC-II and CTA. The 256 MPPCs have 3 mm^2 size, and a peltier cooling system has been developed for uniform and stable cooling down to at least -10 ^{o}C with fluctuations of less than $\pm$0.5^{o}C. The ASIC KI03 charge to time converter developed originally for the JEM-EUSO front-end circuit has been upgraded and adapted for this project. The system is working satisfactorily and will be tested in centi-EUSO (a detector with the same structure as JEM- EUSO, but made at a smaller scale, 74.2 cm $\times$ 40 cm) to demonstrate the ability for cosmic-ray observation. In addition to the JEM-EUSO application, the same camera is also being tested in bio-molecular science to observe molecular dynamics.

4. Other particle physics experiments

SiPMs are employed in many other applications. Two interesting experiments are briefly described.

NEXT is an experiment for neutrinoless double beta decay searches at the Canfranc Underground Laboratory (LSC) [16]. The detector consists of a high-pressure electroluminescence time projection chamber (TPC) filled with gaseous high purity Xenon enriched with Xe-136, with photodetectors at both ends. PMTs on one end provide the energy measurement with the excellent resolution needed for event selection. In addition, a finely segmented MPPC plane behind the anode has been added to perform event tracking. The NEXT-DEMO prototype, which includes a plane with 256 MPPCs of 1 mm^2 size in a 1 cm pitch, has been assembled (Fig. 1). The SiPMs are coated with Tetraphenyl butadiene (TPB) to shift the photon wavelength from UV to blue in order to improve light collection. The system is working successfully and will lead to the development of the NEXT-100 prototype that will include 7500 SiPMs.

The MU-RAY telescope is under development for the study of density variations in volcanoes through muon radiography [17]. The resolution obtained with this method (about 10 m in optimal conditions) is expected to be better than that obtained with gravimetric techniques. The telescope detects horizontal muons through the volcano based on their energy loss in rock, for which the morphology must be known. The detector aims to have a tracking capability with millirad resolution

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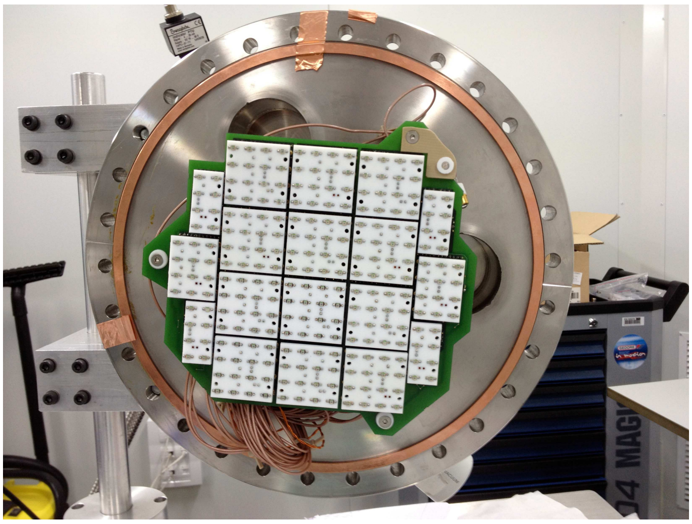

Figure 1: NEXT-DEMO SiPM plane consisting of 256 MPPCs of 1 mm^2 size in a 1 cm pitch, coated with TPB.

at low cost and low power consumption. It should also be resistant and stand temperature variations greater than 60 ^{o}C. Polystyrene scintillators with TiO_2 coating and a WLS fiber, mirrored at one side, are employed. The device should provide sub nanosecond timing resolution. The SiPMs are developed by FBK-IRST, and the SPIROC ASIC from LAL is used in readout. Testing of a 1 m^2 prototype in the laboratory is ongoing, and on-site measurements are planned. The goal is to develop a 10 m^2 prototype for real time and/or stereoscopic observations.

5. Medical applications

The characteristics of SiPMs are well suited to replace PMTs and APDs in medical imaging applications, for example, in intra-operative probes, Single Photon Emission Computed Tomography (SPECT) or Positron Emission Tomography (PET) systems. SiPMs can be employed to replace PMTs or APDs improving the detector performance, or make innovative designs possible. This review concentrates mostly on PET applications, since significant advances have been made in this particular field. Many groups are working on similar developments, and thus only selected examples are given in each case.

The ‘conventional’ PET detector is made of pixellated crystal arrays coupled to position sensitive PMTs, with no information of gamma-ray depth of interaction (DOI) in the crystal, thus leading to parallax errors in the scanners. The use of PMTs makes the combination with magnetic resonance (MR) applications very difficult.

A first fully working ring with SiPMs has been developed and successfully operated employing two types of LGSO crystals of 1.1 mm $\times$ 1.2 mm size and 5 mm/6 mm length in a phoswich configuration that provides DOI determination [18]. Mice have been imaged, and the system is also being tested in PET/MR applications.

SiPMs are also included in other novel system designs with DOI determination. In the X’tal cube detector, SiPMs are placed in all six faces of a cube made of small 1 mm^3 crystals, determining the interaction position in the crystal in 3D [19]. The AX-PET project has developed a parallax-free detector concept [20]. In this detector, LSO crystals of $3 \times 3 \times 100$ mm^3 size are oriented axially (i.e., parallel to the scanner axis), instead of radially (i.e. pointing towards the center of the detector) as they generally are in PET scanners. The stack of several crystal layers provides the desired efficiency while the DOI is determined by the event layer. Crystals are read out by SiPMs from Hamamatsu. In order to obtain the transverse coordinate, WLS fibers, also read out by SiPMs, are placed perpendicularly to the crystals to collect escaping light.

High spatial resolution has been obtained with both pixellated and continuous SiPM-based detectors. Crystal arrays with 0.5 mm^2 crystal size have been resolved employing position sensitive SiPMs developed by RMD [21]. The use of continuous crystals and in particular coupled to SiPMs has gained renewed interest in recent years. Continuous-crystal detectors can achieve better efficiency than those employing pixellated crystals since they avoid the loss of active area due to the separation of the crystals in pixellated arrays. However, determination of the interaction position in the crystal must be carried out with dedicated algorithms. Position determination in 3D (including DOI) is possible, achieving high spatial resolution. Some examples are a spatial resolution of 1.5 mm FWHM achieved with a LYSO crystal of $13.2 \times 13.2 \times 10$ mm ^{3} size coupled to a SensL SiPM array, 4×4 pixels of 3×3 mm^2 in 3.3 mm pitch [22], or a resolution of 0.7 mm FWHM with a $12 \times 12 \times 10$ mm^3 crystal painted white coupled to a monolithic, 64-pixel, SiPM matrix from FBK-IRST with 1.4×1.5 mm pixel size [23].

SiPMs are now considered the 'photodetectors of choice' for the simultaneous combination of PET and magnetic resonance imaging (MRI) modalities. MRI provides a very high resolution anatomical reference for PET with no additional radiation to the patient (as is the case with CT). The HYPERImage and Sublima European projects develop high performance, MR compatible detector blocks for a simultaneous, fully integrated, solid-state PET/MRI system [24].

Fast timing properties make SiPMs good candidates also for time-of-flight (TOF) applications. The determination of the arrival time difference of photons to two opposing detectors operated in time coincidence, makes it possible to restrict the uncertainty of the emission location within the line-of-response (LOR, determined by the interaction points in the two detectors), and thus to reduce the image noise. The position uncertainty in the LOR is given by $\Delta x = c/2\Delta t$ where Δx is the position error, c is the speed of light, and Δt is the error in the timing measurement. A coincidence timing resolution of 101 ps FWHM was achieved with $LaBr_3$:Ce crystals of $3 \times 3 \times 5$ mm^3 size coupled to Hamamatsu MPPCs 3×3 mm^3 [25]. With Cerium and Calcium co-doped LSO (LSO:CeCa) crystals, $2 \times 2 \times 20$ mm^3 also coupled to Hamamatsu MPPCs 3×3 mm^3, a 170 ps FWHM resolution has been obtained employing the NINO ASIC for readout [26].

Digital SiPMs have recently appeared as an alternative to analog SiPMs, and also show promise in medical imaging applications. Excellent spatial and timing resolution has been achieved with a continuous crystal coupled to a Philips Digital SiPM tile [27], and also in the first tests with the AX-PET detectors [20]. The European project Endo-TOFPET-US is also developing Digital SiPMs for the implementation of an endoscopic PET probe for pancreatic and prostatic cancer. The probe, which will work in coincidence with an external system, will be composed of an array of $0.75 \times 0.75 \times 10$ mm^3 LYSO crystals, and will include an ultrasound and tracking sensor [28].

6. Conclusions

SiPMs have shown advantage over other types of photodetectors in many applications, and thus, the number of experiments and groups employing them continues to grow. The improvement of some characteristics (PDE, area, stability, radiation hardness) is still necessary in some areas. The development of new devices is an active field (Digital SiPMs, interpolating SiPMs, UV sensitive SiPMs, sensitivity encoded SiPMs) which also contributes to expanding their use. Interesting developments are still to come.

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