PHILIPS

Technology Backgrounder

PHILIPS' FULLY DIGITAL LIGHT DETECTION TECHNOLOGY

Silicon photomultipliers (SiPMs) have recently gained a lot of interest as replacements for photomultiplier tubes. Like photomultiplier tubes, they are capable of measuring extremely low light levels, to the point of being able to detect single photons. However, compared to photomultiplier tubes, SiPMs offer the 'solid-state' advantages of lower operating voltages, ruggedness, smaller physical size, lighter weight and excellent immunity to magnetic fields.

Nevertheless, current SiPMs do have their limitations. Although they feature very high internal gain, they generate a relatively weak analog output signal that must be processed by a power-hungry readout ASIC (Application-Specific Integrated Circuit) in order to recover the photon count and the time of arrival of the first photon. The cost, size and power consumption of this ASIC makes the transition from using conventional photomultiplier tubes to SiPMs more difficult.

The innovative new all-digital SiPM technology developed by Philips eliminates the need for these external ASICs, opening up the viability of using a solid-state solution in many more applications.

The Philips approach

Although photon counting is by definition a digital task, conventional silicon photomultipliers combine the electrical pulses generated by multiple photon detections into a single analog output signal. As mentioned above, this signal has to be processed by expensive power-consuming electronics in order to recover the photon count.

By integrating low-power CMOS electronics into the silicon photomultiplier chip, the team at Philips has developed a digital silicon photomultiplier in which each photon detection is converted directly into an ultra high speed digital pulse that can be directly counted by on-chip counter circuitry. In contrast to conventional silicon photomultipliers, the Philips digital silicon photomultiplier is therefore an all-digital (digital-in/digital-out) device. As a result, it produces faster and more accurate photon counts with extremely well defined timing of the first photon detection, both of which are important factors in applications such as medical imaging scanners and high-energy nuclear particle detectors.

Moreover, these revolutionary new digital silicon photomultipliers can be manufactured using a conventional CMOS process technology.

Applications

The planar nature of Philips' digital silicon photomultipliers allows them to be closely coupled to suitable scintillator materials for the detection of nuclear particles and high-energy electromagnetic radiation. When struck by an incoming particle or high energy electromagnetic radiation, scintillator materials absorb the energy and re-emit it in the form of a weak flash of light, typically in the visible spectrum. This weak flash of light is then detected by the photomultiplier. Philips' digital silicon photomultipliers are therefore suited for use in particle physics experiments and a wide range of medical imaging equipment, for example in Positron Emission Tomography (PET) scanners.

PET is a molecular imaging technique that produces three-dimensional images of functional processes in the body, e.g. the uptake of glucose that fuels metabolic activity. The PET system detects pairs of gamma rays (high energy electromagnetic radiation) originating from a radioactive tracer, a small amount of which is injected into the patient prior to the scan. To image metabolic activity, PET typically uses a radioactive derivative of glucose called fluorodeoxyglucose (FDG). This compound mimics the behavior of glucose in the body and can be detected by the PET system.

For so-called 'time-of-flight' PET scanners, accurately determining the time at which the first photon arrives at the detector is extremely important. Philips' digital silicon photomultiplier prototypes achieve a timing accuracy for the detection of the first photon of around 190 ps (full-width, half-maximum using a standard scintillator crystal (LYSO) at 511 keV for two detectors in coincidence).

Other applications for Philips digital silicon photomultipliers include fluorescence-based DNA sequencing, protein/DNA microarray assays, surveillance systems and night-vision systems. In fact, almost any application that currently uses photomultiplier tubes for the detection of low light fluxes.

Technology details

Conventional silicon photomultipliers (SiPMs) consist of a two-dimensional array of avalanche photodiodes (APDs) each of which is connected in series with its own polysilicon 'quenching' resistor. All of these diode/resistor 'microcells' are then connected in parallel and the entire microcell array is reverse-biased to a voltage above the diodes' normal breakdown voltage – typically in the range 30V to 70V. Operating in this so-called 'Geiger mode', the diodes are ultra-sensitive to single electron-hole pairs that result in individual diodes experiencing avalanche breakdown. These electron-hole pairs can be generated either by the absorption of a photon (the desired signal), or by thermal energy or electron tunneling (unwanted background noise). The unwanted background noise produced by thermally generated electron-hole pairs and/or electron tunneling, together with false counts due to defective microcells, are collectively referred to as the SiPM's 'dark count'.

To eliminate a conventional SiPM's need for an external digitizing ASIC, the digital silicon photomultiplier developed by Philips equips each individual avalanche photodiode with its own 1-bit on-chip ADC (Analog to Digital Converter) in the form of a CMOS inverter. Each microcell that experiences avalanche breakdown therefore produces its own digital output that is captured, along with the digital outputs from all other triggered microcells, by an on-chip counter. The Philips digital SiPM therefore converts digital events (photon detections) directly into a digital photon count. As a result, it is capable of achieving significantly better resolution than conventional SiPMs.

To overcome the 'dark count' problem associated with conventional SiPMs, each microcell in the Philips digital SiPM is also equipped with an addressable static memory cell that can be used to disable or enable the microcell. Microcells that show high dark count levels can therefore be prevented from contributing false counts to the SiPM's output. This facility allows the Philips' digital SiPM to achieve better signal-to-noise ratios than conventional devices. Because defective microcells in the array can be disabled, it also helps to improve production yield.

Additional circuitry is added to each microcell to actively (rather than passively) ‘quench’ and recharge the microcell after triggering. This active quenching/recharging in the Philips device improves the detector’s recovery time as well as reducing its power consumption. Detector modules constructed using Philips’ new digital SiPM technology typically only require air cooling. Cooling below ambient temperature is only required in applications that require ultra-low dark count levels.

In contrast to conventional analog SiPMs, in which parasitic capacitance and inductance degrade timing performance, all microcells in the Philips' digital SiPM are connected via a low-skew balanced trigger network to an on-chip time-to-digital converter. The timing resolution of this converter is 20 ps, thereby preserving the excellent intrinsic timing performance of the Geiger-mode avalanche photodiodes.

In implementing this new digital SiPM technology, the challenge for Philips was to integrate the relatively high voltage avalanche photodiodes, which must be reverse-biased to around 30V, alongside low-voltage CMOS logic on the same silicon chip, while maintaining dark count and photon sensitivity performance. Nevertheless, the company’s revolutionary new digital SiPMs can still be manufactured using a standard high-volume CMOS process technology.