Silicon photomultiplier technology goes fully-digital

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SILICON PHOTOMULTIPLIERS (SiPMs) based on single photon avalanche diode (SPAD) arrays are capable of measuring extremely low light fluxes, to the point of being able to detect single photons. Compared to traditional photomultiplier tubes (PMTs), they offer the ‘solid-state’ advantages of lower operating voltages, ruggedness, smaller physical size, lighter weight and excellent immunity to magnetic fields.

However, despite the fact that photon counting is essentially a digital task, conventional SiPMs combine the current pulses generated by multiple photon detections (multiple avalanche diode breakdowns) into a weak analog output signal that must be processed by expensive power-consuming external electronics in order to recover the photon count and time-of-arrival of the first photon – figure 1a. In applications where a large number of photomultiplier channels are required, the need for these complex ASICs renders the use of conventional SiPMs impractical.

A fully digital solution

The digital SiPM developed by Philips Digital Photon Counting overcomes most of the drawbacks of conventional ‘analog’ SiPMs by digitally detecting and counting the breakdown of individual SPADs on-chip. The anode of each SPAD is connected to a local CMOS inverter and the outputs of all the inverters in the array are routed to on-chip photon-counting and time-stamping logic. The Philips SiPM is therefore a fully digital (digital in/digital out) device – figure 1b. It is manufactured in a high-volume 180-nm CMOS process and is capable of detecting single photons with a time resolution of 140ps full width at half maximum (FWHM).

At higher photon counts, its time resolution improves to 24ps FWHM. The device has a low temperature coefficient and low power consumption, and is scalable both in detector area and on-chip digital processing.

As in a conventional SiPM, each pixel in the digital silicon photomultiplier comprises an array of SPAD microcells operating in Geiger mode, several volts above their nominal breakdown voltage. However, in the digital silicon photomultiplier, a logic circuit is attached to each SPAD, allowing the microcell to capture, store and output exactly one photon at a time. As soon as an incident photon forces a SPAD microcell into avalanche breakdown, the avalanche is immediately quenched by a dedicated quench transistor.

The CMOS inverter connected to the anode of each SPAD acts as a digital threshold detector. When the SPAD breaks down, the anode experiences a voltage shift approximately equal to the SPAD’s excess reverse bias voltage (the voltage difference between its normal breakdown voltage and the Geiger-mode bias voltage). When the anode voltage reaches the inverter’s threshold voltage, the resulting transition at the inverter output immediately turns on the microcell’s dedicated quenching transistor to stop current flow through the diode. The output of the inverter also generates a high-speed asynchronous trigger and a slower synchronous data output signal, which are bused to the on-chip time-to-digital converter (TDC) and photon counting logic respectively.

The trigger network can be configured to start the TDC on the first photon detection, or on higher photon counts to reduce the effect of dark counts. Embedded refresh logic prevents dark counts from accumulating and reaching the trigger threshold, and also recharges the SPADs by turning on each microcell’s dedicated recharge transistor. In addition, row and column addressing allows the triggered status of each microcell to be read out.

Subdividing each pixel into a number of sub-pixels, each with its own trigger logic, allows trigger validation and photon counting schemes to be tailored to specific applications. For example, armed with knowledge about the photon generation characteristics of a particular scintillator crystal (such as the initial density of photons), it is possible to implement statistical trigger validation schemes that can discriminate between scintillation in the crystal and dark count.

Dark count rate

In addition to the circuitry described above, each microcell in Philips’ digital silicon photomultiplier has an addressable latch to enable/disable the cell. This ability to selectively activate and deactivate each microcell allows detailed characterization of basic sensor parameters such as breakdown voltage,
sensitivity, time resolution, trigger network skew and dark count rate. For example, by programming the device to trigger on the first photon and enabling each microcell in turn, a dark count rate (DCR) map for the entire SPAD array can be compiled – see figure 2. Typically, only very few diodes contribute significantly to the total dark count rate, which means that the device’s overall DCR can be dramatically improved by disabling these microcells. This capability also improves production yield, because a few defective microcells need not make the device unusable. Being able to accurately map defective microcells also enables systematic defects to be identified and corrected in future production runs.

**Photon detection efficiency**

A photomultiplier’s photon detection efficiency (PDE) is a measure of the probability of detecting a photon of a certain wavelength. Various factors influence PDE, among them being the quantum efficiency of silicon, the avalanche generation probability and the fill factor of the detector. While the quantum efficiency of silicon is very high in the visible region of the spectrum, the avalanche generation probability is strongly dependent on the internal design of the SPADs, for example, on their electric field strength profiles and carrier type.

The fill factor depends on the lateral design of the device and especially on the area taken up by each microcell’s threshold detection and control circuitry. In some applications, the use of microlenses can mitigate loss of PDE due to fill factor. Increasing the cell size also helps to increase the fill factor at the cost of earlier saturation of the pixel. The PDE of the Philips digital SiPM test chip is shown in figure 3, where it should be noted that the illustrated response below 400nm and above 720nm wavelengths is a limitation of the test set-up, not of the device itself.

One phenomenon that can occur to a lesser or greater extent in all SiPMs is avalanche breakdown in one SPAD producing additional photons that initiate secondary breakdowns in neighboring SPADs. The probability of photon generation in a SPAD is directly proportional to the current density in the high field-strength region of the diode junction. It can therefore be reduced by reducing the diode current. In Philips’ digital SiPM, this is achieved by the dedicated active quenching transistors and the microcell’s circuit topology. Optical crosstalk reduction is also enhanced in the Philips device by the use of deep-trench isolation, which helps to shield each SPAD from its neighbors.

If the device contains a few SPADs with a high DCR, the optical crosstalk can be quantified, because these SPADs can be used as photon generators. The measurement technique involves looking for coincidence between breakdowns in neighboring SPADs and those in the photon-generating SPAD and then adjusting for the known DCR of the neighboring SPADs.

**Temperature sensitivity**

Conventional analog SiPMs suffer from a considerable degree of temperature sensitivity, due largely to the temperature dependence of the ionization coefficients of electrons and holes in silicon. This results in temperature dependent drift in the SPAD’s breakdown voltage and a significant change in gain. However, the digital SiPM is relatively insensitive to such variations because the shift in breakdown voltage has to exceed the threshold voltage of the CMOS inverter before it affects the count rate.

Any residual temperature sensitivity in the digital SiPM is largely due to the temperature dependence of photon detection efficiency, which can only be compensated for by adapting the bias voltage of the device. However, it may be possible to integrate a programmable bias voltage generator and a temperature sensor or breakdown voltage detector onto the chip in order to provide automatic temperature compensation.

The temperature dependence of the test chip in terms of both PDE and time-to-digital converter performance have been measured using an attenuated picosecond laser delivering approximately 2100 photons per pulse. The observed drift in the average number of counted photons per pulse over a range of 15 to 25°C was -0.33 percent/°C – figure 4a – an order of magnitude lower than that for analog SiPMs. Drift in the time-to-digital converter was 15.3 ps/°C – see figure 4b.

The contributions of individual system components to the absolute time resolution of the digital SiPM were investigated separately at low and high photon fluxes. The contribution of the time-to-digital converter to the time resolution is 20ps FWHM and under low light flux conditions the SPAD contributes 548ps FWHM, mainly due to the avalanche spreading uncertainty. Negligible jitter was measured, but a significant systematic skew of 1.10ps FWHM was detected in the trigger network. Manual fine-tuning of the on-chip trigger network is currently being performed to eliminate this skew.

**Applications**

The digital SiPM is suitable for use in a wide range of applications where PMTs or analog SiPMs are currently being used. The planar nature of the devices allows them to be closely coupled to suitable scintillator materials for the detection of nuclear particles and high-energy electromagnetic radiation. The high level of on-chip digital integration, which eliminates the need for complex external signal processing, and their minimal cooling requirement means that they can be tiled closely together to produce large-area detectors, such as those needed in medical PET scanners. Other applications include fluorescence-based DNA sequencing, protein/DNA microarray assays, surveillance systems and possibly also night-vision systems.