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Tiled Silicon Photomultipliers for large area, low light sensing applications

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ABSTRACT

Large area optical detection systems are required for applications including cell imaging, spectroscopy, nuclear medicine, bio diagnostics, radiation detection and high energy physics. Each of these applications requires that a detector or detector arrays be closely coupled with light sources or optical couplers such as fibres or light couplers. In this paper, the scaling of novel Silicon Photomultiplier detectors to tile across a large area is presented. In particular, a novel method is discussed for compact packaging of SPM detectors into a tiled 2D detector array for large area imaging and 2D spatial detection. The SPM detector has performance characteristics comparable to vacuum photon multiplier tubes used in these applications today but offers several performance and system design advantages including spatial resolution, optical over exposure, small form factor, weight, magnetic insensitivity and low bias operation.

Keywords: Silicon Photomultiplier, large area detector arrays, multi-anode PMT.

1. INTRODUCTION

Advances in sensors [1] together with smart optoelectronic interconnect solutions are needed for applications which require 2D arrayed sensor elements for large area detection or position sensitive systems. Applications include nuclear medicine, general spectroscopy and real time fluorescence detection systems for bio-applications. These applications require the development of a new generation of smart optical sensor modules with low light level sensitivity, high spatial resolution and large area. For both large area and 2D spatial detection the Silicon Photomultiplier (SPM) [2-4] is a relatively new sensor which is particularly attractive as an alternative to traditional detectors such as Intensified Charge Coupled Devices - ICCD's (slow recording speeds for real time detection) and PMT-based solutions (robustness, sensitivity to magnetics and high operating voltages).

In this paper, we highlight developments in SPM technology and discuss current applications. SPM detectors are currently limited to detector sizes of the order to several millimeters square. To compete with PMT, large area detection comparable to the typical PMT area of ~1" sizes and greater is required. It is desirable to address the scaling of individual SPM detectors to tile across a large area to develop a large area detection surface. The challenges facing the SPM in terms of large area assembly and electronics are discussed and developments based on a novel thin film flex architecture is presented. Flex circuitry and its associated printing techniques is well suited as an interconnect medium and has become widely accepted for many applications which require light weight flexible substrates which can be manufactured using roll to roll printing techniques. Examples are numerous and include RFID's, smart card biometrics, organic solar cells for photovoltaics and 'roll-up' display for large electronic maps, pages or miniature projectors.

2. SPM TECHNOLOGY AND APPLICATIONS

The Silicon Photomultiplier (SPM) [2-4] is an extension of the concept of the Geiger-Mode avalanche photodiode (GAPD) [5]. Geiger mode operation is achieved by biasing the diode above breakdown. At these bias levels the electric field at the junction is so high that a single carrier generated in the depletion region causes an avalanche where the whole diode goes into breakdown and causes large current flow. Such a breakdown is referred to as a Geiger breakdown. In this 'on' state, the diode will continue to generate current, as the avalanche is self perpetuating, until it is quenched in some way to turn it back to its 'off' or sensitive state. This quenching can be most easily achieved with a large series resistance that limits the current and provides feedback to lower the voltage and turn off the avalanche. Due to the sensitivity to each single electron produced in the active volume, and the corresponding large gain produced in this 'Geiger mode', such devices are sensitive to single photons. The current flowing is fixed regardless of the initial number of electrons that caused the breakdown, and can therefore be thought of as a logic signal. Therefore, such a GAPD is ideal as a single photon counting device.

A novel way to extend the concept of the GAPD is to provide an output signal proportional to the input photon flux. The SPM structure referred to a cell in this paper is based on MxN pixel array of GAPD diodes that individually act as photon counters, see Fig. 1. In Geiger mode the individual APD diodes are biased beyond electrical breakdown and the generated carriers acquire sufficient energy to result in a self-sustaining avalanche current flow. The current flow is limited by individual quench resistors, which turns off the breakdown to reset the diode. When all of the outputs are multiplexed together, the total device behaves like a proportional, 'analogue' device for photon fluxes. When a photon flux is incident upon the surface of this GAPD matrix, the number of pixels activated, and hence the size of the output current, is directly proportional to the number of incident photons. The SPM output is proportional and linear for $N_{photoelectrons} < N_{cells.}$ The multi-cell structure essentially converts a binary device into an analogue device capable of measuring photon flux

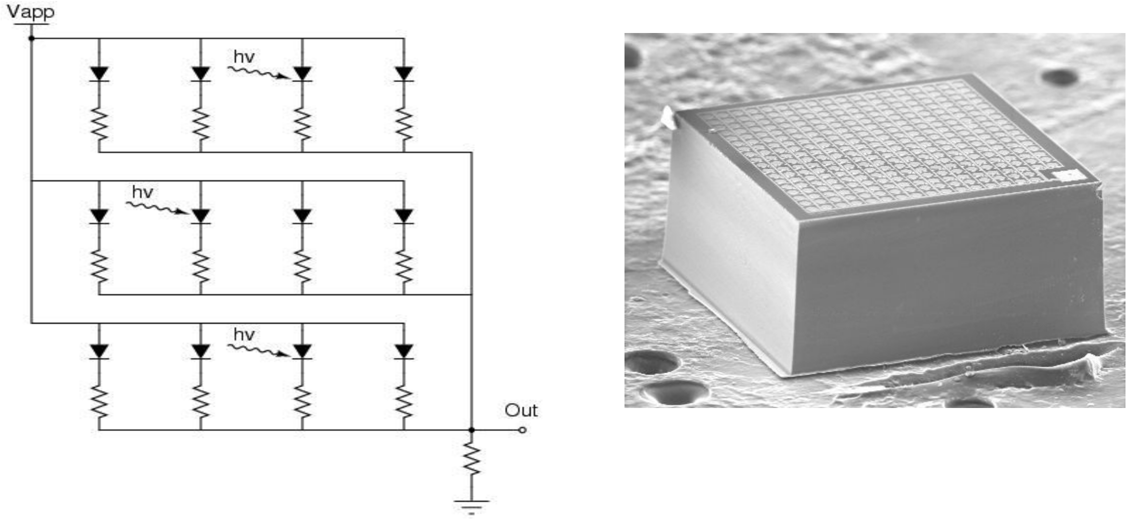


Fig. 1. Left, SPM structure showing array of Geiger mode APD diodes with individual quench resistors connected in parallel; right, SensL's fabricated 1mm^2 SPM consisting of 600-1000 pixels depending on design.

The SPM detector has performance characteristics comparable to PMT devices and overcomes many of their operational limitations including robustness, magnetic sensitivity, ambient light sensitivity and high bias operation. The main benefits include

- The ability to design very sensitive, yet compact, sensors for hand-held instruments. The form factor of the detector along with its front-end electronics is very small compared with that associated with a conventional PMT tube.
- The deployment of sensors which are immune to fluctuating magnetic fields, require only low bias voltage supply and consume very little power. These characteristics present unique opportunities for their use in the large-scale deployment of ubiquitous sensors.
- Detection of the single photoelectron response which allows discrimination between photon numbers incident on the detector.
- Compared to PMT's, the detector can be exposed to ambient light without damage.
- Compatible with CMOS integrated circuit manufacture.

Applications include

- Nuclear medicine: the ability to integrate radiological imaging techniques into a single sophisticated multi-modality imaging system, example include Positron Emission tomography (PET) [6] with Magnetic Resonance Imaging (MRI). The form factor of the SPM allows the possibility of having a finer spatial resolution and higher packing density of detectors. In addition, the transit time spread of SPM detectors can be small, of the order of 100ps which is important for PET scanners which use time is the coincidence timing between two signals to reduce statistical noise in image reconstructions. The fast timing of the SPM also offers the possibility of Time of Flight (ToF) systems that would further improve the image quality.
- Bioapplications: The SPM is a promising candidate for use in cell imaging and biodiagnostic equipment – e.g replacing ICCD's and multi-anode PMT in hand held biosensing applications such as real time fluorescence detection.
- Portal Radiation Detection Homeland security: The ability to improve the spectral resolution and sensitivity performance of large-volume plastic scintillators for portal monitor applications and for the development of new hand-held spectrometers having a sensitivity 10 to 20 times greater more sensitive that those currently used.
- SPM technology is a promising candidate to integrate directly large area arrays of detectors to scintillators in magnetic environment typically in the region of 2-5T; examples include electromagnetic calorimeters [7] where PMTs would need to placed outside the , some meters away, incurring the addition of large lengths of optical fiber and degrading the signal.

2.1. SPM PERFORMANCE

SPM are currently fabricated upto a few square mm. The main characteristics of 1mm^2 and 9mm^2 SPM detectors from SensL are listed in Table I. The SPM detector is operated either at room temperature or cooled (typ. -20-30°C) and can operate with pulsed or transimpedance pre-amplification for pulsed and continuous signal inputs respectively.

SPM detectors are calibrated by measuring their photo-electron spectrum, which is a histogram of the charge measured during period that coincides with the SPM receiving a low light signal pulse, see Fig. 2. When the light impinges on the detector, some SPMs pixel fire and the integrated charge is recorded. This measurement is then repeated many times. Due to poisson statistics of the photons and the PDE of the SPM, the number of pixels that fire will vary from measurement to measurement. On average a small integer number of pixels will fire but there is also a finite probability that 0, 1, 3, 4, etc pixels will fire. By repeating the measurement many times a record of the charge recorded from 0, 1, 2, 3 etc pixels is built up. Due to the low noise and well defined gain of the SPM, a histogram of the charge data results in well defined peaks corresponding to the number of pixels firing. On occasions when no pixels fired the integrated charge is small and is due to noise of the system i.e leakage current shot noise, amplifier noise etc. This charge forms the first peak of the spectrum and is referred to as the pedestal.

Table I: Typical SPM specifications of SensL's current 1mm^2 and 9mm^2 detectors.

Parameter	Value
Sensitive Area (mm^2)	1, 9
Bias Voltage (V)	27-28
Gain (above breakdown)	10^6
No of Pixels	1000 (1mm^2), 4000 (9mm^2)
QE pixel %	40 (λ_{peak} = 520nm)
Photon Detection Efficiency (PDE, (%)[*]	15-22

[*] PDE is defined here the photon detection probability (PDP) times fill factor [5].

The photo-electron spectrum also provides a means of calibrating the SPM in terms of gain (photoelectron peak separation), noise contributions and for a known optical signal the photon detection efficiency. The well resolved peaks are indicative of the low noise and uniform, stable gain of the Geiger mode APDs. The quantised nature of the peaks is not generally observed in PMT spectra due to the excess noise and variable nature of the amplification.

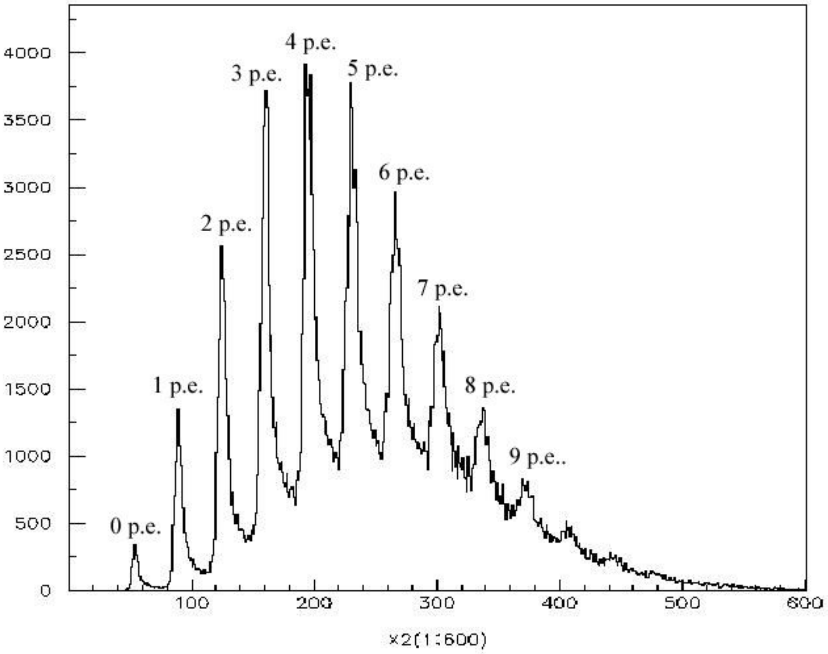


Fig. 2. Single Photoelectron Spectrum for SensL's 1mm^2 SPM detector.

3. SPM ARRAYS

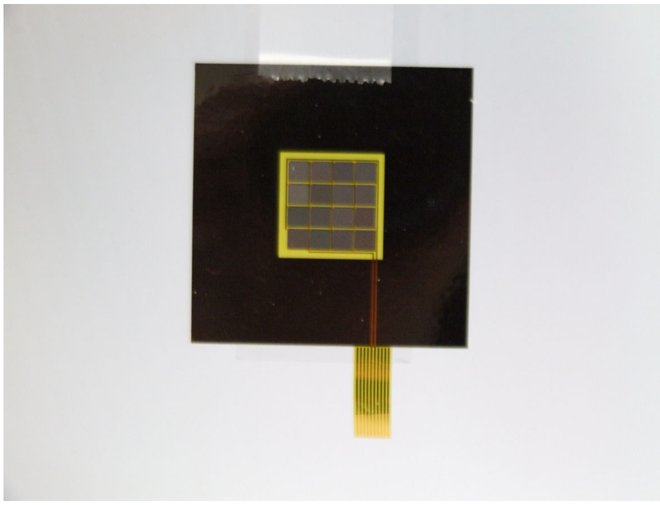
Optoelectronic interconnect solution is required which support high fidelity low cost, light weight connections to each element within an array such that all elements are either individually or collectively addressed. The single detector acts as a zero dimension detector without any spatial information. A tile array of detectors in an NxN array format offers 2D detection with spatial information in X and Y directions.

The requirements of the packaging solution requires the need to avoid

- use of wirebonds and wirebond passivation which are fragile and not mechanically robust for large detector arrays. In addition, the passivation material usually polymer coatings suffer from yellowing with age thereby degrading transmission properties of the detector system.
- elaborate post processing of the SPM detector for electrical interconnection. Examples include via through hole etch and metallisation (plating) for through-hole vias.
- complex and expensive techniques using backside illumination which requires back thinning at wafer level.
- combinations of large and small solder bumps for flip-chip assembly.
- expensive ceramics carriers and glass lids.

3.1. LARGE AREA ARRAYS

Fig. 3 shows a novel approach to tiling sixteen 9mm^2 SPM detectors mounted in a 4x4 array configuration [8]. The outputs of the tiles are summed together resulting in a sensor with a large active area - the first high gain silicon alternative to large area PMT's. The detectors are packaged in a format suitable for direct coupling to light sources such as scintillators and light couplers.



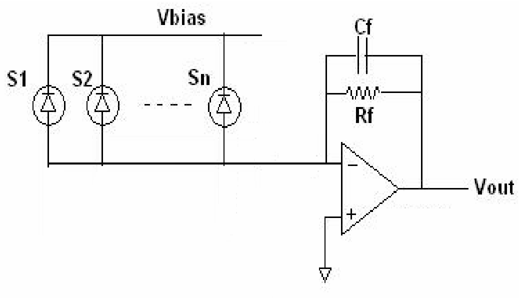


Fig. 3. Left 4x4 array of tiled SPM detectors mounted on flex using flip-chip bonding and Right: Schematic of summed array output using transimpedance amplification

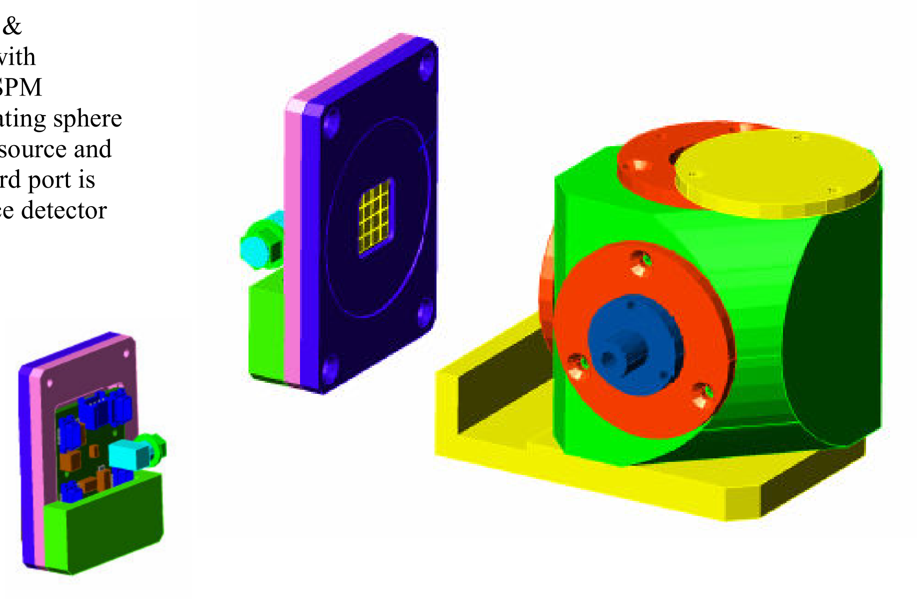
The detectors were Au stud bumped at wafer level. During shear testing a shear force of 40±2 CN was measured. The detectors were subsequently mounted on thin film flexible printed circuit board based on a polyimide based substrate with Cu metal tracks which are gold finished. In this example, a 4x4 array of detectors are tiled and mounted on the flex using thermocompression flip-chip bond with a detector pitch of 3.2mm (200µm spacing). For other applications, such as microarray readers a 1xN array is required with a spacing between the detectors which is typically 1mm. The use of flex is compatible with higher-density flex circuit technology using large array sizes N>5. Multilayer metal flex circuits are more appropriate construction choice as the metal is buried and routed to the outside of the circuit via multiple buried interconnect layers.

The raw SPM array output signal requires a number of processing steps before it is ready for data processing. These include amplification, shaping and buffering (output impedance matching). In this paper, a transimpedance (pre-amplification) board was connected to the output of the array. The preamplification stage allows the voltage across the detecting device to be held constant thereby eliminating the need for charging and discharging of external parasitic capacitances. This method is particularly useful with summed array in Fig. 3 where the detector signals are combined to produce a single output. The diagram in Fig. 4 shows the simplest arrangement with the detector anodes feeding the input of the transimpedance amplifier. The amplifier gain is governed by the resistor Rf and is set typically between 470 Ω and 1500Ω. The gain can be stated in mV/mA as between 470 and 1500. The amplifier can be implemented in a number of ways. At present a standard part, which provides acceptable speed and stability, was implemented.

3.2. EXPERIMENTAL SETUP AND RESULTS

The 4x4 array was tested using a 3 port miniature integrating sphere from SphereOptics [9]. A pulsed white LED was connected to the 0° port to provide a spatially uniform light signal to the SPM array which was connected to the 90° port. An optional 3rd port (north pole) can be used for viewing or reference detector for calibration purposes, see Fig. 4.

Fig.4. SPM Module showing 4x4 array & transimpedance amplifier together with experimental approach to measure SPM performance using miniature integrating sphere with fiber input port for pulse LED source and output port for light detection. A third port is optional for viewing and/or reference detector measurements.



The current dependence on the applied bias for the summed arrayed output was performed. Fig. 5 The IV curve shows nAmp leakage below breakdown with a uniform breakdown at 27V.

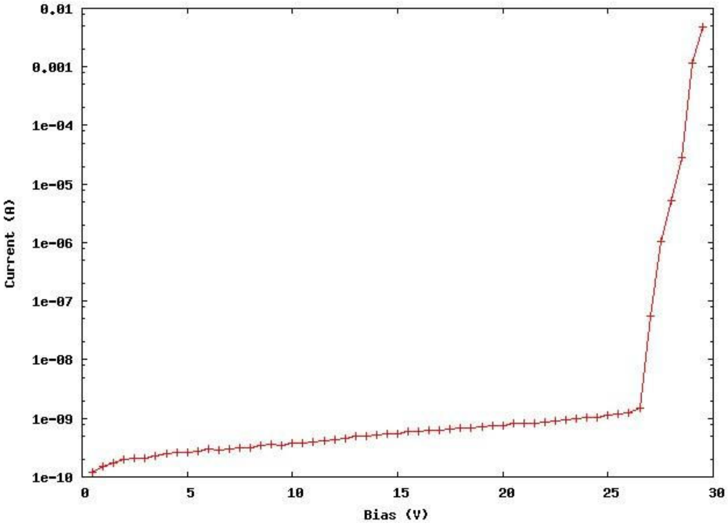
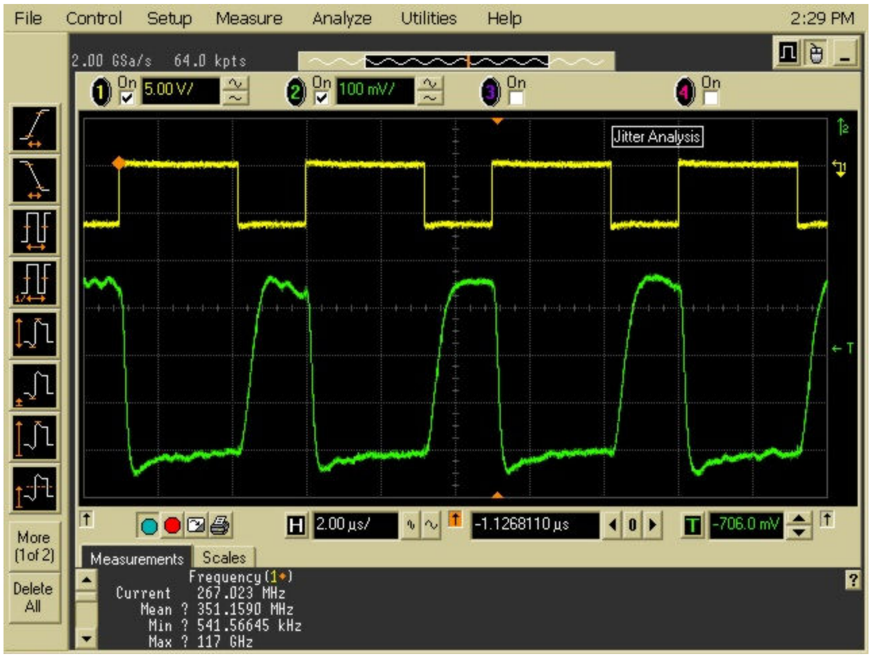


Fig. 5. IV plot for 4x4 SPM array.

The optical response of the summed detector was tested at 32V, +4V above voltage breakdown, see Fig. 6. Onset response times were of the order of tens of nanoseconds with the signal quickly reaching saturation at >+2V output which is the rail of the board.



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              Frequency(1•)
Current    267.023 MHz
   Mean ? 351.1590 MHz
    Min ? 541.56645 kHz
    Max ? 117 GHz
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Fig. 6. Pulsed LED output (top trace) and SPM array detector response (bottom trace).

4. CONCLUSIONS

In this paper, the need for large area high gain detection based on an alternative to the vacuum PMT has been highlighted. The SPM detector represents a solid state alternative which has many benefits for several applications identified. Currently, SPM detector sizes are limited to 1mm x1mm. In this paper, a novel NXN array package is presented and initial results have shown the potential of this technology for large area detection and 2D spatial resolution.

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