

STMicroelectronics Silicon PhotoMultipliers

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Outline 2

- SPAD and SiPM working principles
- ST SiPM structure
- SiPM main characteristics
- Noise
- Detection efficiency
- Time resolution
- ST portfolio
- Applications and funded projects



SPAD Working Principle 3



- Photodiode biased above its breakdown voltage;
- Due to the high electrical field in the depletion layer, a primary charge carrier thermally or photo-generated can trigger an avalanche event;
- A sharp current pulse with sub-nanosecond rise time and a few mA peak value is produced;
- This mode of operation is commonly known as Geiger-Mode.



SPAD Working Principle

 $t_A t_B$

 t_C



 $t < t_o$ no carrier in the depletion region $\rightarrow i=0$ $t=t_o$ a carrier (photogenerated or thermally generated) initiates the avalanche $t < t_o < t_1$ the avalanche current spreads over all the active area $\rightarrow 0 < i < l_{max}$ $t > t_1$ self-sustaining current





APD versus SPAD

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- Bias: slightly BELOW breakdown
- Linear-mode: it's an amplifier
- Gain = (Electrons out)/(Photons in)

- Bias: ABOVE breakdown
- Geiger-mode: it's a trigger device
- Very high gain !!!



SiPM Working Principle



SiPM structure is based on a bidimensional pixel array of SPAD pixels (cells) each of which connected to an integrated decoupling quenching resistor.

Each cell operates as an independent photon counter (Geiger Mode) and gives the same signal when fired by a photon.

Since all the cells work on a common load, the amount of charge collected at the SiPM output is given by the analog superposition of the binary signals produced by all the fired pixels. SPAD gives no information on light intensity; The Geiger-mode limitation can be overcome by the Silicon PhotoMultiplier.





Excellent photon resolving power for weak photon fluxes



- thode layerTuneable anti-reflection coatingDedicated gettering techniques
- Thin optical trench with metal filling
- Shallow dead layer (< 0.2 um)

Poly-silicon resistors

life.augmented

SiPM reverse characteristic





SiPM forward characteristic

life.auamontod

Breakdown Voltage vs. Temperature 10

Pulse Shape 11

Oscilloscope Persistence Pictures ¹²

Measured in a few photons illumination conditions at 3V OV

Very good single photoelectron resolution measured on all the tested devices.

Such resolution is not allowed in large area devices.

Experimental setup 13

The gain (G) is defined as the average amount of charge (Q) flowing in the photodiode during the avalanche event divided by the elementary charge (e).

 $G=Q/e=(V_{BIAS}-V_{BD})C_D/e$

Valid for few Volts above V_{BD} .

- 100 microcells SiPM, 45% fill factor, 58 µm active area side
- Laser illumination (1KHz repetition rate)
- 50 ns gate time window

We extracted the values of all parasitic elements in the cell and in the array. Then we developed detailed analytical and numerical models.

Parameter	Unit	SPM10-60N
Sensitive area size	mm ²	1.08 × 1.08
Cells matrix dimension		17 × 17
Number of cells		324
Cell fill factor	%	45
Cell size	μm²	60 × 60
Cell C _d @ 3 Volt OV	fF	193
Cell R _d	Ω	240
Cell C _q	fF	10
Cell R _q	KΩ	320
Gain @ 3 Volt OV		3.8⋅10 ⁶

Dark Count 18

- Thermal generation of charge carriers produces current pulses (dark count pulses) even in the absence of illumination.
- According to the Shockley-Read-Hall (SRH) theory, the thermal generation of electron-hole pairs in the depletion region is due to generation recombination (GR) centers, i.e. localized levels with energy at about mid gap.
- Other relevant contributions to the dark count can be given by the diffusion in the junction depletion layer of electrical carriers thermally generated in quasi neutral regions.

Light emission from silicon

Avalanche processes in Silicon produce light. The amount of produced light is very low, on the order of only 10⁵ photon per electron in the avalanche. Typically one operates a SiPM at a gain of 10⁶, which produces a few tens of photons.

Measured differential light emission spectrum from Si avalanche. The stars mark the peak wavelengths of the LEDs used for the calibration.

R. Mirzoyan et. Al. / Nuclear Instruments and Methods in Physics Research A 610 (2009) 98-100

Schematic representation of the optical crosstalk effect.

Direct cross talk ²⁰

ST-SiPM Direct cross talk < 1% (0 < OV < 5 Volt)

Optical crosstalk suppression \rightarrow Trenches filled with Tungsten

Delayed cross talk ²¹

Two different SiPM technologies

p/n structure

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p⁺ common anode

n⁺ common cathode

Layout compatible with both technologies

Photon Detection Efficiency 23

In a SiPM the Photon Detection Efficiency (PDE) is defined as the ratio between the rate of output pulses exceeding the device's dark noise rate and the rate of impinging photons. The **PDE** is given by the product of the quantum efficiency **QE** of the active area, the geometric fill factor $\boldsymbol{\varepsilon}$ and the probability that an incoming photon triggers a breakdown $P_{trigger}$.

 $PDE = QE \times \varepsilon \times P_{triager}$

- The quantum efficiency **QE** represents the probability that an incoming photon is absorbed in the active area of the device.

• The geometrical fill factor $\boldsymbol{\varepsilon}$ is defined as the ratio of the active to total area of the microcell.

The triggering probability P_{trigger} is the probability that an electron-hole pair triggers a self-sustaining avalanche in the depletion region. It strongly depends on the overvoltage.

Photon detection efficiency (PDE) 24

✓ **p/n** structure is better for **blue** light detection.

✓ n/p is better for green-red light detection

Experimental setup for PDE measurements **25**

Courtesy of : G. Bonanno (INAF)

Cell-edge shrinkage

life.augmented

Numerical simulations made with ATLAS code

Potential lines and electric field color plot scale.

 $V_{cathode} = 30$ Volt

With a careful study of the structure we reduced the cell edge to **5 microns**, improving the fill factor and the PDE

Photon Detection Efficiency improvement 27

PDE almost doubled moving from N-on-P to P-on-N high fill factor technology. PDE at OV > 5 Volts still increasing in all technologies ST-SiPM PDE up to 40% (60 micron cell pitch)

SPTR Spectra (405 nm, 5V OV)

Time resolution **28**

4x4 mm² SiPMs, 4100 microcells, 45% fill factor, BV≈28 V, RQ ≈265 KΩ

Single photon timing resolution (SPTR) spectra measured in single photon regime. The timing resolution is defined as the sigma of the Gaussian fit to the timing distribution.

P on N devices have higher triggering probability \rightarrow process of avalanche buildup becomes faster and with reduced statistical fluctuations \rightarrow The intrinsic timing response is faster.

SPTR Measurements (405 nm)

Time resolution - SPTR

Measurement of the SPTR of the SPM10-60. There is good agreement between the HPTDC measurement (after the time resolution of the HPTDC has been subtracted) and the oscilloscope measurement

Courtesy of: K. Doroud (CERN)

Time resolution (jitter)

Time resolution as a function of the number of detected photons.

Courtesy of: P. Jarron (CERN)

Coincidence Resolving Time 31

SMD package 32

Top view

Bottom view

Plastic package with transparent resin

Very compact package:

(5 mm x 5.5 mm x 0.7 mm)

Low stress

Cross section

<u>Left</u>: Front side of the module, showing the 81 quad pixel packaged SiPMs (4SPM20-60N).

<u>Right</u>: Backside of the module showing the connectors .

SiPM portfolio (2)

Large	
SPM42H6-40	SPM42H5.5-60
SPM42H6-50	SPM42H5-60
SPM42H6-60	
SPM42H6-75	
SPM42H6-100	

Small	
SPM10H6-40	SPM10H5.5-60
SPM10H6-50	SPM10H5-60
SPM10H6-60	
SPM10H6-75	
SPM10H6-100	

2 x 2 arrays
4SPM20H6-60
4SPM20H5.5-60

Protein immunoassays

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An example of scanner for immunoassay. It is a confocal microscopy with a stage for mechanical scanning of the macro-arrays.

Fluorescence detection

Photomultiplier tubes (PMT) are the most widely used sensors in the state-of-the-art microarray analysis systems.

The PMT measures the light emitted by a pixel (much smaller than a spot) and the image is acquired by scanning the observed point over the microarray area.

Confocal microscopy is the most sensitive instrument for microarray analysis.

But it is massive and relatively slow

Example of image obtained with the Scanarray. Si/SiO2 slide spotted with fluorophores at several different concentrations

Fluorescence: Device Sensitivity

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SiPM 3x3 cells (150mm)

Size equivalent to the spotted drop of proteins

Preliminary results of experiments with arrays of small SiPMs

We used an array of small SiPMs, optically coupled (one to one) to the protein spots. The SiPMs are read in parallel (without mechanical scanning). This set-up simplifies the optical system, allows miniaturization and permits good sensitivity.

Sensitivity ~ 0.1 pgr (for IgG proteins) Suitable for applications like: IgE immunoassay - [allergy] TSH immunoassay - [thyroid]

SiPM advantages in fluorescence detection 39

- Very good sensitivity;
- Very simple optical and mechanical system (no laser, no photomultiplier tubes, no scanning);
- Analysis of many different proteins in parallel (up to ~ 100 probes in 1 cm²);
- Low bias (compared to PMT): ~ 30 Volt;
- Simple read-out electronics; parallel read-out
- Fully automated data analysis, no need of images post-processing
- Cheap platform;
- Compact, weight light;
- Can be battery operated;

Funded projects – CSI (2010 – 2013) 40

Project full title: Central Nervous System Imaging

Beneficiaries: STMicroelectronics-Italy, Philips Applied Technologies, Philips HealthCare, University of Bologna, IMEC, Gtec, AIT, etc.

Topics: Silicon sensors for nuclear medicine (SiPM), RF technology for high resolution MRI, Active electrodes for 3D brain electrical imaging

ENIAC JOINT UNDERTAKING Sub-program: Nanoelectronics for Health and Wellness

Small Animal PET scanner prototype

SiPMs for CSI 41

Front side of the module, showing the 81 packaged devices (4SPM20-62N).

- The new detection modules (crystals + SiPM + readout electronics) have been fabricated and tested.
 - The performances are equivalent to those of PMT.
 - Probably this detection module can be used also for SPECT.

Funded projects – High Profile (2011 – 2013) 42

Project full title: High-throughput Production of functional 3D images of the brain

Beneficiaries: Philips HealthCare, STMicroelectronics-Italy, University of Bologna, Philips Applied Technologies, FEI Electron Optics International B.V., Gtech, AIT, Eagle Vision, VTT, etc.

Topics: image diagnostic platforms for the central nervous system, EEG, EIT, MRI, **Near Infrared Imaging**

ARTEMIS JOINT UNDERTAKING

Sub-program: Healthcare systems

Cap with EEG probes

Human brain imaging using near-infrared light

Intrinsic chromophores and structures of the brain.

For human brain imaging, near-infrared light will penetrate more readily through the scalp and skull to sample the brain thanks to lower scatter and absorption. Spectra: major chromophores in brain are oxy- and deoxyhemoglobin.

NIR system conceptual blocks

High profile 44

Conceptual design of the tissue cap with light sources and detectors

Funded projects – Muon Portal (2011 – 2014)

Project full title: Portale per il contrasto del contrabbando di materiale fissile nucleare (Nuclear screening portal system designed to identify and interdict the contraband of nuclear devices and materials)

Beneficiaries: STMicroelectronics,

Università di Catania, INAF (National Institute of Astrophysics), MIWT, Insirio

Topics: System designed to identify fissile elements, like Uranium and Plutonium, inside cargo containers. The equipment utilizes the natural cosmic rays background (muons) as probe and a large number of SiPMs as detectors.

> Programma Operativo Nazionale Ricerca e Competitività 2007 - 2013

Currently deployed X-ray radiography systems are limited because they cannot be used on occupied vehicles and the energy

We will build an equipment that overcomes these limitations by obtaining tomographic images using the scattering of cosmic radiation as it transits each cargo container.

X-ray and gamma ray portals 46

Over 120 million vehicles enter the United States each year. Many are capable of transporting hidden nuclear weapons or nuclear material.

because they cannot be used on occupied vehicles and the energy and dose are too low to penetrate many cargos. We will build an equipment that overcomes these limitations by obtaining tomographic images using

Muon portal 47

The Earth is continuously bombarded by energetic stable particles, mostly protons. These interact in the upper atmosphere through the nuclear force, producing cascades of secondary particles, whose most penetrating component are the muons. The flux at sea level is about 1 muon/(cm² min) in an energy and angular range useful for tomography. We will use a suitable detector technology: strips of plastic scintillators coupled with SiPMs.

Muon interrogation is selective to high-Z materials, both nuclear material and high-Z shielding materials. The trajectory of a charged particle through any material is the result of the convolution of many small deflections due to Coulomb scattering from the charge of the atomic nuclei in the medium. The angular deflection of the trajectory is very sensitive to the charge (Z) of the atomic nuclei.

Layout and mechanical structure of the muon tomograph

Each plan is made from hundreds of scintillator strips. When a muon pass through the scintillator, a burst of photon is generated. They travel to the strip-ends and they are detected by the SiPMs.

As a detection system, we plan to build a large muon tracker consisting of 8 planes, 6 m long and 3 m wide, large enough for the inspection of standard containers.

Results of simulations demonstrate the possibility of reaching detection times of few minutes.

Funded projects – PicoSEC (2011 – 2014) 49

Project full title: Pico-second Silicon photomultiplier Electronics & Crystal research Marie Curie Network

Beneficiaries: CERN, TU-Delft, Desy, Fibercryst, UHEI, Kloè, LIP, UNIMIB, TUM, **STMicroelectronics**, SurgicEye

Topics: training program for young researchers in multidisciplinary R&D projects geared to develop a new class of ultra-fast photon detectors in PET (Positron Emission Tomography). Scientific fields: optic for fast timing, photodetectors, electronics and data acquisition, endoscopic instrumentation.

SEVENTH FRAMEWORK PROGRAMME The PEOPLE Programme

Conclusions 50

- ST developed n-on-p and p-on-n SiPM technologies with almost equivalent performances. We obtained direct comparison of detection efficiency. For the detection of blue light it is confirmed the superiority of p-on-n version. For infrared light the n-on-p version could be the better choice.
- We showed some examples of equipment prototypes that will incorporate the SiPM. The low cost of this silicon device open many new opportunities.

