Fully Integrated Arrays of Digital SiPMs - the Way towards Industrial Application
Solid State, Digitization and Integration Always Win

Transistor  Television  Photography  Telephony

X-Ray imaging  Next: Light Detection
Disruptive Technology: what does it change?

Television/Monitor

- form factor (geometry, size, shape)
- **system design** (external & internal)
- power consumption
- heat dissipation
- depth of integration
- safety, durability, stability
- performance/cost ratio
- performance/weight ratio
- distribution/ NEW markets
- **WAY of USE**

- internet on TV
- wall hanging
- TV on mobile phones
- displays everywhere

Light Detection

- high performance ToF
- PET/MR
- intra-operative PET
- organ specific PET
- 3D imaging
PHILIPS

Truly Disruptive Technology……

- is SCALABLE
- allows simpler designs
- consumes less power
- dissipates less heat
- allows higher depth of integration (reduces no. of components)
- is safe, robust, durable & stable
- has better
  - performance/cost ratio
  - performance/weight ratio
- allows wider distribution/use
- opens NEW markets/applications
- changes the way we USE technology

All factors need to be considered
(Not only) for fast scintillators a fast reacting light detector is desired

Graphs courtesy of Spanoudaki & Levin, Stanford, in Sensors, 10, 2010
Motivation: A better detector for Positron- Emission- Tomography (PET) with Time-of-flight (TOF) 

Acquisition time

1 min

3 min

CRT >1ns 500 ps 250 ps 100 ps

Non-ToF

ToF (500 ps)

5 min.

3 min.

2 min.

1 min.

The optimal detector for Positron-Emission-Tomography (PET) provides TOF and DOI detection.

TOF – time-of-flight
DOI – depth of interaction

High sensitivity → long crystals
High spatial resolution → small cross section
High aspect ratio → needs DOI

PET with TOF and DOI implemented with PMT’s

Uses 4-layer scintillator → expensive!

Nakazawa et. al., in: Nuclear Science Symposium Conference Record (NSS/MIC), 2010 IEEE

CRT = 442 ps FWHM

Fig. 13  Reconstructed images with/-without-DOI-TOF
(a) nonDOI-nonTOF,  (b) DOI-nonTOF,
(c) nonDOI-TOF,    (d) DOI-TOF
## Scintillation light detectors

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“Therefore, while the APD is a linear amplifier for the input optical signal with limited gain, the SPAD is a trigger device so the gain concept is meaningless.” (source: Wikipedia)
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Digital Photon Counting: Realization

analog SiPM

Summing all cell outputs leads to an analog output signal and limited performance

digital SiPM (dSiPM)

Integrated readout electronics is the key element to superior detector performance

Digital output of
• Number of photons
• Time-stamp
Analog vs. Digital SiPM: Layout

**Analog Silicon Photomultiplier Detector**

![Analog SiPM Diagram]

- SiPM
- $V_{\text{bias}}$
- Readout ASIC
- Discriminator
- TDC
- Shaper
- Integral
- ADC
- Time
- Energy

**Digital Silicon Photomultiplier Detector**

![Digital SiPM Diagram]

- Cell Electronics
- Recharge
- Trigger Network
- TDC
- Photon Counter
- Time
- Energy

*Detector + Readout*
PDPC dSiPM: Architecture and Pixel Diagram

Single pixel

Die (2x2 pixel)

(smart) tile (8x8 pixel)
Highly integrated arrays of dSiPMs

DLS-3200-22-44
DLS-6400-22-44

**FPGA**
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

**Flash**
- FPGA firmware
- Configuration
- Inhibit memory maps

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Power & Bias

200 MHz ref. clock

Serial configuration interface

Serial Data output (x2)
PDPC dSiPM versions

**DLS 6400-22**
- 6400 cells per pixel
- 59 x 32 μm cell size
- 54% fill-factor

**DLS 3200-22**
- 3200 cells per pixel
- 59 x 64 μm cell size
- 78% fill-factor
Measurement setup (1&2)

dSiPM array

Clock, Config, Data

Electronic trigger

Psec-laser

dSiPM array

Clock, Config, Data

USB connection

PC
Intrinsic Timing Resolution

**DLS-6400-22-44**

- Timestamp difference (ps)
- Counts (arb. u.)
- Counts (arb. u.)
- 44 ps FWHM

**DLS-3200-22-44**

- Timestamp difference (ps)
- Counts (arb. u.)
- Counts (arb. u.)
- 55 ps FWHM

**DLS-6400-22-44**

- Timestamp difference (ps)
- Counts (arb. u.)
- Counts (arb. u.)
- 59 ps FWHM

**DLS-3200-22-44**

- Timestamp difference (ps)
- Counts (k)
- Counts (k)
- 104 ps FWHM
Measurement setup (3)

- LYSO scintillator array
- dSiPM array
- Clock, Config, Data
- USB connection
- PC

- 22Na
- Clock, Config, Data
- dSiPM array

©Philips Digital Photon Counting, October 2011
Scintillator readout – single die, short xtal
Timing resolution

3 mm x 3 mm x 5 mm Ca co-doped LSO:Ce on PDPC demonstrator chip

Photograph of Ca co-doped LSO:Ce crystal mounted on dSiPM demonstrator chip

- Time difference spectrum measured with a Na-22 point source
- CRT = 120 ps FWHM (for two detectors in coincidence) at room temperature

D.R. Schaar et al, NSS-MIC 2011, MIC15.S-137
Scintillator readout – full array (tile), long xtal

Timing resolution

- LYSO array, 8 x 8 crystals, 4 mm x 4 mm pitch, **22 mm length**
- DLS-3200-22-44
- Measurement taken at +10°C

Timing resolution per pixel

**Summed histogram over all pixels**

- 286 ps FWHM
Scintillator readout

Energy resolution

- LYSO array, 8 x 8 crystals, 4 mm x 4 mm pitch, 22 mm length
- DLS-3200-22-44
- Measurement taken at +10°C

Energy resolution per pixel

Summed histogram over all 64 pixels
Digitization results in Significantly Reduced Temperature Sensitivity

- **24 ps** full-width at half-maximum timing resolution of ps-laser
- Photopeak changes **0.33%** per degree C due to changing PDE (values of analog SiPM’s are ranging from 2-8%)
- Time changes **15.3 ps** per degree C (TDC + trigger network drift)
- PDE drift can be easily compensated by adapting the bias voltage
- TDC offset can be periodically re-calibrated using the SYNC input
Optical Crosstalk

DLS-6400-22

- Approx. 8% optical crosstalk

DLS-3200-22

- Approx. 18% optical crosstalk

→ Has to be taken into account in saturation correction
• Dark count rate at 20°C, 3.3V excess voltage
• Average dark count rate ~ 550cps per SPAD (150 kHz/mm²)
• Scales with SPAD sensitive area
Spectral Sensitivity DLS-6400-22-44

Effective PDE:
- LYSO(Ce) 25.9%
- CsI(Na) 23.7%
- CsI(Tl) 20.5%
- NaI(Tl) 24.2%
- BGO 24.2%
- LaBr$_3$(Ce) 9.6%

- Peak PDE ~30% at 430 nm and 3.3 V excess voltage
- Conservative diode design (54% fill-factor)
- No anti reflection coating used
**PDPC dSiPM: Linearity only affected by Saturation → Correction Possible**

\[ p = -N \cdot \ln\left(1 - \frac{k}{N}\right) \]

- **N**: active cells (6400)
- **k**: triggered cells
- **p**: # of photons

- Experiments taken at room temperature
- No temperature stabilization
- Correction not possible on analog SiPMs
PDPC dSiPM: Dark Count Mapping/Tuning

- Dark counts per second at 20°C and 3.3V excess voltage
- ~ 95% good diodes (dark count rate close to average)
- Typical dark count rate at 20°C and 3.3V excess voltage: ~150Hz / diode
- Dark count rate drops to ~1-2Hz per diode at -40°C
- Cells with high DC can be switched off individually → DC control
PDPC dSiPM: slow scan imaging mode

- Spatial sampling of the light distribution
- Similar to dark count map measurement
- Dark count map can be used for correction
- Alternatively, use coincidence to reduce noise
- Potentially useful for light guide design
PDPC dSiPM: Small Crystal Readout

LYSO array, 30 x 30 crystals, 1 mm x 1 mm pitch, 10 mm length

Data analysis by P. Düppenbecker, Philips Research
Highres Monolithic Crystal Readout

Reference detector

X-Y stage

Collimator

24 mm x 24 mm x 10 mm LSO:Ce,Ca on PDPC array
Highres Monolithic Crystal Readout

0.98 mm FWHM and 2.31 mm FWTM average resolution

- Improved nearest neighbors method (HT van Dam et al, in review, IEEE TNS)
- 100 reference events per calibration position
- Measurement performed at 0 °C.
Highres Monolithic Crystal Readout

- Average energy resolution: ~11.5% FWHM
- Negligible saturation
PDPC dSiPM: (PET) Detector Module
advanced integration

- Modular design incl. 2 x 2 tiles
- Integrated cooling
- Module PCB for data concentration, processing & corrections
- List mode or raw data output
- full ring under construction
PDPC: Integrated sensors/detectors workflow

- Sensor design (PDPC)
- Silicon processing (180 nm fab, 38 masks, > 500 steps)
- Die testing (PDPC)
- Tile manufacturing (packaging experts)
- Tile testing (PDPC)
- Scintillator attachment (packaging experts)
- Module assembly (packaging experts)
- Final module testing (PDPC), overall system design
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A Digital Light Sensor will be useful beyond PET

Medical Imaging
- Focus Nuclear Imaging
- Pre-clinical PET&SPECT imaging
- Clinical PET imaging
- Intra-operative probes
- Clinical SPECT imaging
- PET/MR
- Low dose CT
- Spectral CT

Other Medical Imaging
- PET imaging
- SPECT imaging
- PET&SPECT imaging
- Clinical PET imaging
- Intra-operative probes
- Clinical SPECT imaging
- PET/MR
- Low dose CT
- Spectral CT

Adjacent opportunities
- Analytical Instrumentation
  - DNA Sequencing
  - Microscopy
  - Microarrays
  - LoC
- High Energy Physics
  - Antineutrino Detection
  - Particle Accelerators
  - Cherenkov Detectors
- Night Vision / Surveillance / Security
  - Automotive Night Vision
  - Facility / Homeland Security
  - LIDAR
Philips Digital Photon Counting

Your entry to exploring the technology…

PDPC-TEK (Technology Evaluation Kit)
Launched Q2/11-available now!
PDPC dSiPM @ NSS-MIC

(Mo., 16:30) N4-1, Mean and Variance of the Response of Digital SiPM-Based Scintillation Detectors: Model and Measurements
H. T. van Dam, S. Seifert, G. J. van der Lei, D. R. Schaar
delft University of Technology, Delft, The Netherlands

(Mo., 17:00) N4-3, Highly Integrated Arrays of Digital SiPMs with Simplified Readout Interface
C. Degenhardt, B. Zwaans, O. Muelhens, R. de Gruyter, T. Frach
Philips Digital Photon Counting, Aachen, Germany

MIC15.S-83, First Performance Measurements of Monolithic Scintillators Coupled to Digital SiPM Arrays for TOF-PET
G. J. van der Lei, H. T. van Dam, S. Seifert, D. R. Schaar
Radiation detection and Medical Imaging, Delft University of Technology, Delft, Netherlands

D. R. Schaar, H. T. van Dam, G. J. van der Lei, S. Seifert
Radiation Detection & Medical Imaging, Delft University of Technology, Delft, The Netherlands

NP5.S-154, Timing Methods for Monolithic Scintillator Detectors Based on Digital SiPM Arrays
H. T. van Dam, S. Seifert, G. J. van der Lei, D. R. Schaar
delft University of Technology, Delft, The Netherlands

(Tue., 15:00) J1-3, Investigation of a Sub-Millimeter Resolution PET Detector with Depth of Interaction Encoding Using Digital SiPM Single Sided Readout
P. M. Dueppenbecker, L. Sodome, P. K. Marsden, V. Schulz
1Philips Research Europe, Aachen, DE, 2King's College London, London, UK, 3RWTH Aachen University, Aachen, DE

(Wed., 17:15) MIC5-4, A Method for Measuring the Sub-Pixel Light Distribution of Scintillation Detectors with Digital SiPMs
P. M. Dueppenbecker, R. Haagen, L. Sodome, P. K. Marsden, V. Schulz
1Philips Research Europe, Aachen, DE, 2King's College London, London, UK, 3RWTH Aachen University, Aachen, DE
Thursday, October 27th, 7 p.m. @ Instituto Valenciano de Arte Moderno

C. Degenhardt (Philips):
Advanced Integration in Digital Light Sensors: Arrays and Modules

R. Schulze (Philips):
The PDPC Technology Evaluation Kit (TEK): Your Entrance to Digital Photon Counting

Dennis R. Schaart (TU Delft):
Initial Experience with Digital SiPMs for Time-of-Flight PET