Development of MPPC

ELPH 研究会 C010 「素粒子・原子核実験における全吸収型カロリメーターの実例と応用」
HAMAMATSU detectors for high energy physics
CERN  LHC (Large Hadron Collider)

underground 100m, circumference 27km and with the ability to collide the proton and proton of energy to maximum 7TeV.

provided from CERN experiment groups
ATLAS - SSD

Solid State Division

provided from CERN experiment groups
The principle and structure of SSD

When a particle enters the SSD, electron-hole pairs are generated along the track. (around 20,000 electron-hole pairs for 300 um Si) The electrons drift towards the N-side and holes drift towards the P side by internal electric field. In Figure, the output from the P-side electrode in accordance with the position is obtained.

SSD has PN junction arranged in stripes on high resistivity Si substrate, and normally used at full depletion by applying voltage.
ATLAS Central tracking detectors & SCT module

Hybrid with ASICs
40 mrad

768 strips 80μm間隔

TPG baseboard with BeO facings

128 mm

provided from CERN experiment groups
CMS - SSD

31 Nations, 150 Institutions, 1870 Scientists

**TRIGGER & DATA ACQUISITION**
Austria, CERN, Finland, France, Greece, Hungary, Italy, Korea, Poland, Portugal, Switzerland, UK, USA

**TRACKER**
Austria, Belgium, CERN, Finland, France, Germany, Italy, Japan*, Switzerland, UK, USA

**CRYSTAL ECAL**
Belarus, CERN, China, Croatia, Cyprus, France, Italy, Japan*, Portugal, Russia, Switzerland, UK, USA

**RETURN YOKE**
Barrel: Czech Rep., Estonia, Germany, Greece, Russia
Endcap: Japan*, USA

**SUPERCONDUCTING MAGNET**
All countries in CMS contribute to Magnet financing in particular: Finland, France, Italy, Japan*, Korea, Switzerland, USA

**HCAL**
Barrel: Bulgaria, India, Spain*, USA
Endcap: Belarus, Bulgaria, Russia, Ukraine
HO: India

**FEET**
Pakistan, China

**FORWARD CALORIMETER**
Hungary, Iran, Russia, Turkey, USA

**MUON CHAMBERS**
Barrel: Austria, Bulgaria, CERN, China, Germany, Hungary, Italy, Spain,
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

* Only through industrial contracts

Total weight: 12500 T
Overall diameter: 15.0 m
Overall length: 21.5 m
Magnetic field: 4 Tesla

provided from CERN experiment groups
CMS-Si tracker and SSD

1 Sensor on 6 inch wafer

S9153, S9154 series

provided from CERN experiment groups
CMS - APD

31 Nations, 150 Institutions, 1870 Scientists

provided from CERN experiment groups
Type of Si-APD

**reach-through type**

Reach-through type is suitable for the detection of long wavelength like red light.

**reverse type**

Reverse type is suitable for the detection of short wavelength like blue light.

⇒ For scintillation detector or a low-energy X-ray direct detector, p + surface incident and thin dead layer is necessary.
Characteristics required for the CMS-APD

- **APD is used in a high magnetic field** ⇒ require to operate at high magnetic field

- **Blue light from crystal is weak.** ⇒ require high blue sensitivity and low noise

- **Radiation hit directly to APD.** ⇒ require high radiation tolerance (2E13 n-eq/cm²) and less sensitive to incident radiation background

- **APD needs large area to cover a crystal**

- **APD are controlled from outside the accelerator** ⇒ require low bias dependence and easy to control
Specifications and Structure of CMS-APD

- Blue sensitivity improved by SiN-AR coating
- Low-capacity by spreading the depletion layer into the N side
- Thin absorbing layer for less sensitive to incident radiation
- V-Groove for less increase of surface leakage current due to the irradiation damage.

<table>
<thead>
<tr>
<th>Spec. (Ta = 25°C)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>STD No</strong></td>
<td>S8148</td>
</tr>
<tr>
<td><strong>active area</strong></td>
<td>5 x 5 mm²</td>
</tr>
<tr>
<td><strong>breakdown voltage (VB)</strong></td>
<td>&gt; 325 V</td>
</tr>
<tr>
<td><strong>Operating Voltage (VR)</strong></td>
<td>300 – 450 V</td>
</tr>
<tr>
<td><strong>Difference VB–VR</strong></td>
<td>&gt; 25 V</td>
</tr>
<tr>
<td><strong>Dark current at VR</strong></td>
<td>&lt; 50 nA</td>
</tr>
<tr>
<td><strong>Capacitance at VR</strong></td>
<td>65 – 85 pF</td>
</tr>
<tr>
<td><strong>Quantum efficiency at VR, 430nm</strong></td>
<td>75 ± 5%</td>
</tr>
<tr>
<td><strong>Passivation layer</strong></td>
<td>SiN</td>
</tr>
<tr>
<td><strong>Protective coating</strong></td>
<td>Epoxy Resin</td>
</tr>
</tbody>
</table>
VB & VR distribution of S8148

The σ of VB and VR is almost same (σ: around 17V).
The distribution of VB-VR is very small(σ: around 1.3V).
The distribution of dark current is good and much smaller than specification.

The variation of Ct is small.
History of MPPC development
MPPC Technology Overview

➢ What is an MPPC?
- Multi-Pixel Photon Counter
  a new type of photon-counting device
  made up of multiple APD pixels
  operated in Geiger mode

➢ Features
- Small size / light weight
- Room temperature operation
- Low bias operation: ~70V
- High gain: $10^5$ to $10^6$
- Excellent timing resolution
-Insensitive to magnetic fields
- Simple readout circuit operation
Principle of operation

➢ Basic operation
- Each pixel operates separately in Geiger-mode
- Each pixel outputs a same amplitude pulse
- Pulse generated by multiple pixels are output while superimposed onto each other (detected at the same time)
- No position information
**Geiger-mode operation**

APD

Quenching resistor

**Output current [A]**

**Reverse Voltage [V]**

- **Geiger mode region**
- **Vop: Operating voltage**
- **V_{BR}: Breakdown voltage**

**Vov: Over voltage**

\[ Vov = Vop - V_{BR} \]
MPPC for precision measurement

MPPC for general measurement
2006 released

⇒ Main application:
multi-photon measurement: PET
High energy physics

Precision measurement application

MPPC for precision measurement
2013 released

- Low dark !
- Low after pulse !
- Higher PDE !
**MPPC for T2K Experiment (2008)**

**Required properties**
- Good coupling to φ1mm fiber
- High PDE for 525nm
- Withstand high magnetic field
- Low dark count

S10362-13-050C
Installed 56kpcs.

(Provided from Kyoto University)
MPPC for general measurement

**Required properties**
- High time resolution (TOF/PET)
- Withstand high magnetic field (PET/MR)
- Large detection area
- Small dead space
- 4-side buttable package

S12642-0404PA
MPPC Characteristics improvement
Latest Development

Noise

2007
1st generation (S10362 series)

2013
2nd generation (S1257x series) w/ Low afterpulse

2014
2015

Latest (S1308x series) w/ Low crosstalk

Newest w/ High Fill factor

Sensitivity (PDE)
Low After Pulses

Example of After pulse suppression

After pulse probability has been suppressed by optimization of structure and material.

All new MPPC series have very lower after pulses compared with conventional type.
Crosstalk Suppression by Trench isolation

Low cross talk series each MPPC micro cell is surrounded by an optical trench isolation.

It prevents penetration of generated secondary photons to neighboring micro cells.
## Characteristics

3x3 mm² MPPC 50μm pitch at 3V overvoltage

<table>
<thead>
<tr>
<th>Sample</th>
<th>Crosstalk</th>
<th>Dark Count</th>
<th>Fill Factor</th>
<th>PDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>S12572-050C</td>
<td>44%</td>
<td>1 Mcps</td>
<td>62%</td>
<td>35%</td>
</tr>
<tr>
<td>S13082-050CS</td>
<td>3%</td>
<td>0.5 Mcps</td>
<td>61%</td>
<td>35%</td>
</tr>
<tr>
<td>S13360-3050CE</td>
<td>3%</td>
<td>0.5 Mcps</td>
<td>74%</td>
<td>40%</td>
</tr>
</tbody>
</table>
Gain Comparison

3x3 mm² 50µm pitch

Overvoltage (V) vs. Gain for 1st gen. (S10362), 2nd gen. (S12572), and Newest (S13360)
PDE comparison

3x3 mm² 50μm pitch

Overvoltage (V)
PDE (%) 1st gen.
2nd gen.
NEW: S13360

1st: S10362
2nd: S12572
NEW: S13360

PDE (%) vs. Overvoltage (V) graph for 3x3 mm² 50μm pitch with PDE comparison for 1st gen, 2nd gen, and NEW: S13360.
Crosstalk comparison

3x3 mm² 50μm pitch

- **1st**: S10362
- **2nd**: S12572
- **NEW**: S13360
Dark Count Comparison

Solid State Division

3x3 mm² 50μm pitch

Overvoltage (V)

Dark Count (kcps)

1st gen.
2nd gen.
Newest

10
100
1000
10000

1st: S10362
2nd: S12572
NEW: S13360
After pulse comparison

3x3 mm² 50μm pitch

- 1st: S10362
- 2nd: S12572
- NEW: S13360
Pulse height distribution comparison

1\textsuperscript{st}: S10362

2\textsuperscript{nd}: S12572

NEW: S13360

3x3 mm\textsuperscript{2} 50μm pitch
Dynamic range of MPPC
Dynamic range of MPPC

MPPC maximum output is determined by:

- Large number of MPPC pixels.
- Short recovery time

*Demerit*

Small pixel $\Rightarrow$ Small fill factor, Low PDE
Dynamic range by readout method of MPPC

Photosensitive area : 3x3mm

Counting Mode

Analog mode

Difference by maximum count rate

Difference by PDE

Difference by noise & PDE

Incident photons (cps)

Output (cps)

50um pitch

10um pitch

Recovery time
Dynamic range by readout method of MPPC

Photosensitive area: 3x3mm

Incident photons (cps)

Output (cps)

- 50um pitch
- 10um pitch

Analog Mode

Difference by PDE

Difference by pixel number & recovery time

Difference by noise & PDE

Counting mode
Large area MPPC
Large photosensitive area (MPPC array)

- 1mm□ 1ch
- 3mm□ 1ch
- 3mm□ 4x4ch discrete array

3-side buttable

- 3mm□ 4x4ch monolithic array with wire bonding
  S11828 series

4-side buttable

- 3mm□ 4x4ch discrete array with TSV
  S13361-3050 series

Low after pulse & Low Crosstalk
Through Silicon Via technology (TSV)

Cross section of TSV

Photosensitive area: 3x3mm$^2$
50μm pitch

Dead Area: 0.4%
Radiation hardness
Dark Current / (Gain * PDE)

HPK 10 samples
Red markers

Other 6 makers
(A to F)
MPPC STD line up
New MPPC Standard line up in 2015

Standard Product series

**General (Low after pulse)**
(S1257x series)
10, 15um
25, 50, 100um

**Precision (Low cross talk)**
(S1336x series)
25, 50um

Applications

**High dynamic range**

**Precision measurement**

**Academic Research**
(L-Xe, L-Ar, etc)

**Midium noise**
Low cost

*Under development!*

*New*
Available in Apr., 2015
## MPPC line up of LCT series

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Active Area</th>
<th>Pixel pitch</th>
<th>Package</th>
<th>Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>S13360-1325CS</td>
<td>□1.3 mm</td>
<td></td>
<td>Ceramic</td>
<td>Silicone</td>
</tr>
<tr>
<td>50CS</td>
<td></td>
<td>25 μm 50 μm</td>
<td>SMD</td>
<td>Epoxy</td>
</tr>
<tr>
<td>-1325PE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50PE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-3025CS</td>
<td>□3.0 mm</td>
<td></td>
<td>Ceramic</td>
<td>Silicone</td>
</tr>
<tr>
<td>50CS</td>
<td></td>
<td>25 μm 50 μm</td>
<td>SMD</td>
<td>Epoxy</td>
</tr>
<tr>
<td>-3025CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-6025CS</td>
<td>□6.0 mm</td>
<td></td>
<td>Ceramic</td>
<td>Silicone</td>
</tr>
<tr>
<td>50CS</td>
<td></td>
<td>25 μm 50 μm</td>
<td>SMD</td>
<td>Epoxy</td>
</tr>
<tr>
<td>-6025CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50CS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## MPPC line up of LCT series

<table>
<thead>
<tr>
<th>Type No.</th>
<th>Active Area</th>
<th>Pixel pitch</th>
<th>Array ch.</th>
<th>Connector</th>
<th>Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>S13361-3050NE-04</td>
<td>□3.0 mm</td>
<td>50 μm</td>
<td>4 x 4 ch</td>
<td>No</td>
<td>Epoxy</td>
</tr>
<tr>
<td>AS-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silicone</td>
</tr>
<tr>
<td>S13361-3050NE-04</td>
<td>□3.0 mm</td>
<td>50 μm</td>
<td>4 x 4 ch</td>
<td>Yes</td>
<td>Epoxy</td>
</tr>
<tr>
<td>AS-04</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silicone</td>
</tr>
<tr>
<td>S13361-3050NE-08</td>
<td>□3.0 mm</td>
<td>50 μm</td>
<td>8 x 8 ch</td>
<td>No</td>
<td>Epoxy</td>
</tr>
<tr>
<td>AS-08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silicone</td>
</tr>
<tr>
<td>S13361-3050NE-08</td>
<td>□3.0 mm</td>
<td>50 μm</td>
<td>8 x 8 ch</td>
<td>Yes</td>
<td>Epoxy</td>
</tr>
<tr>
<td>AS-08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silicone</td>
</tr>
</tbody>
</table>
Custom MPPC for High energy physics / Academic research
MPPC for CMS HCAL upgrade (HB/HE)

Required properties
- Low dark count
- Radiation hardness
- High PDE
- Wide dynamic range, Short recovery time
- Sensitive area: φ3.3mmx8ch 15μm pitch
MPPC for LHCb SciFi Tracker

**Required properties**
- Coupled with SciFi matrix
- 64x2ch fine pitch MPPC array
- Sensitive area: 0.23x1.5mm ±0.25mm
- High position accuracy
- High PDE @400nm
MPPC for Cherenkov Telescope Array

Required properties
- High PDE @300nm
- High Gain
- Low cross talk
- Low dark count
- Large sensitive area
- Sensitive area: 6mm 4ch Hexagonal

\(\lambda > 290\text{nm}\)

Light guides

S12516
MPPC for MEG Upgrade

MEG experiment: searching for $\mu^+ \rightarrow e^+ + \gamma$ decay
Liquid xenon $\gamma$-ray detector will be upgraded
2” PMT $\rightarrow$ MPPC for VUV (175nm) total 4,000pcs.

Required properties
- Sensitive area: 6x6mm, 4ch discrete
- With quartz cover glass
- High PDE in VUV (175nm)
- Low dark count
- Low crosstalk
- Low temp. operation (< -100°C)

Pictures from Tokyo University

S10943-3186
Thank you for your attention!

jp.hamamatsu.com