Current status of Hamamatsu Si detectors mainly for High Energy Physics Experiments

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December 2017

HAMAMATSU PHOTONICS K.K.
Solid State Division
Outline

1. SSD (Silicon Strip Detector) for tracker of many HEP experiments
2. Development of large area PAD detector
3. APD (Avalanche Photo Diode) for LHC-CMS
4. MPPC® (Multi Pixel Photon Counter) for HEP application
5. MPPC® for medical application
Hamamatsu Si detectors for HEP

Particle detection
Silicon Strip Detector (SSD)
Silicon Pixel Detector
Silicon PAD Detector

Photo detection
Silicon Photo Diode (PD)
Silicon Avalanche Diode (APD)
Multi Pixel Photon Counter (MPPC®)
1. SSD (Silicon Strip Detector) for tracker of many HEP experiments

2. Development of large area PAD detector

3. APD (Avalanche Photo Diode) for LHC-CMS

4. MPPC® (Multi Pixel Photon Counter) for HEP application

5. MPPC® for medical application
# Review of main SSDs made by Hamamatsu (~1999)

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>DETECTOR TYPE</th>
<th>size</th>
<th>QTY.</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>MARK II</td>
<td>DC-SSD 3type</td>
<td>3chip/4inch</td>
<td>44</td>
<td>1987</td>
</tr>
<tr>
<td>CLEO II</td>
<td>AC-SSD 3type</td>
<td>1chip/4inch</td>
<td>122</td>
<td>1993～1994</td>
</tr>
<tr>
<td></td>
<td>Psides: punch-through, Nside: poly-Si &amp; DML</td>
<td>2chip/4inch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELPHI</td>
<td>AC-SSD 2type</td>
<td>2chip/4inch</td>
<td>130</td>
<td>1993～1994</td>
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<tr>
<td></td>
<td>both-side: poly-Si, Nside: DML</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELPHI up grade</td>
<td>AC-SSD, FOXFET</td>
<td>2chip/4inch</td>
<td>330</td>
<td>1994</td>
</tr>
<tr>
<td>NOMAD</td>
<td>AC-SSD, FOXFET</td>
<td>2chip/4inch</td>
<td>650</td>
<td>1996～1997</td>
</tr>
<tr>
<td>CLEO III</td>
<td>DC-SSD, Psides: DML</td>
<td>2chip/4inch</td>
<td>550</td>
<td>1997～1999</td>
</tr>
<tr>
<td>CDF-SVX</td>
<td>AC-SSD 3type</td>
<td>1chip/4inch</td>
<td>360</td>
<td>1997～1999</td>
</tr>
<tr>
<td></td>
<td>both-side: poly-Si, Nside: DML</td>
<td>2chip/4inch</td>
<td></td>
<td></td>
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<tr>
<td>CDF-ISL</td>
<td>AC-SSD</td>
<td>1chip/4inch</td>
<td>550</td>
<td>1998～1999</td>
</tr>
<tr>
<td></td>
<td>both-side: poly-Si, Psides: stereo</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>PAMELA</td>
<td>AC-SSD</td>
<td>2chip/4inch</td>
<td>60</td>
<td>1997</td>
</tr>
<tr>
<td></td>
<td>Psides: punch-through, Nside: poly-Si &amp; DML</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>KEK-B(BELLE)</td>
<td>AC-SSD</td>
<td>2chip/4inch</td>
<td>180</td>
<td>1998</td>
</tr>
<tr>
<td></td>
<td>both-side: poly-Si, Nside: DML</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZEUS</td>
<td>AC-SSD 3type, poly-Si</td>
<td>1chip/4inch</td>
<td>950</td>
<td>1999</td>
</tr>
</tbody>
</table>
### Review of main SSDs made by Hamamatsu (2000～)

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>DETECTOR TYPE</th>
<th>size</th>
<th>QTY.</th>
<th>period</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGILE</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>500</td>
<td>2000</td>
</tr>
<tr>
<td>PAMELA</td>
<td>DC-SSSD</td>
<td>1chip/6inch</td>
<td>300</td>
<td>2000</td>
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<tr>
<td>BELLE up grade</td>
<td>AC-DSSD, both-side: poly-Si</td>
<td>2chip/4inch</td>
<td>250</td>
<td>2000～2002</td>
</tr>
<tr>
<td>ATLAS</td>
<td>AC-SSSD 6type, poly-Si</td>
<td>1chip/4inch</td>
<td>15500</td>
<td>2001～2003</td>
</tr>
<tr>
<td>GLAST</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>11500</td>
<td>2001～2003</td>
</tr>
<tr>
<td>CMS</td>
<td>AC-SSSD 14type, poly-Si</td>
<td>1chip/6inch</td>
<td>24000</td>
<td>2003～2006</td>
</tr>
<tr>
<td>LHC-b</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>560</td>
<td>2005～2006</td>
</tr>
<tr>
<td>ALICE</td>
<td>AC-SSSD 2type, poly-Si</td>
<td>1chip/6inch</td>
<td>106</td>
<td>2005～2006</td>
</tr>
<tr>
<td>Phenix</td>
<td>Strippixel, DML</td>
<td>3chip/6inch</td>
<td>600</td>
<td>2007</td>
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<tr>
<td>PP2PP</td>
<td>AC-SSSD 2type, poly-Si</td>
<td>1chip/6inch</td>
<td>120</td>
<td>2003～2007</td>
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<tr>
<td>FVTX</td>
<td>AC-SSSD 2type, poly-Si</td>
<td>3chip/6inch</td>
<td>450</td>
<td>2009～2010</td>
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<tr>
<td>STAR-HFT</td>
<td>AC-SSSD, poly-Si</td>
<td>2chip/6inch</td>
<td>216</td>
<td>2012</td>
</tr>
<tr>
<td>HALL-B</td>
<td>AC-SSSD (stereo) 3type, poly-Si</td>
<td>1chip/6inch</td>
<td>434</td>
<td>2012</td>
</tr>
<tr>
<td>BELLE-II</td>
<td>AC-DSSD 2type, Poly-Si</td>
<td>1chip/6inch</td>
<td>265</td>
<td>2011～2014</td>
</tr>
<tr>
<td>DAMPE</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>768</td>
<td>2014</td>
</tr>
</tbody>
</table>
ATLAS-SSSDs

- Poly-Si resistor
- Bias ring
- Guard ring
- DC-PAD
- AC-PAD

AC coupling-SSSD

1 Sensor on 4 inch wafer

6 type of S8536 series

provided from ATLAS experiment groups
CMS-SSSDs

1 Sensor on 6 inch wafer

S9153, S9154 series

provided from CERN experiment groups
Fermi(GLAST)-SSSD

Total strip detectors: 11,000 pcs
8.95x8.95 mm 228μm pitch

provided from GLAST experiment groups
Belle - DSSD

Double Side SSD (DSSD) from 6inch wafer

Belle Detector

provided from Belle experiment groups
1. SSD (Silicon Strip Detector) for tracker of many HEP experiments

2. Development of large area PAD detector

3. APD (Avalanche Photo Diode) for LHC-CMS

4. MPPC® (Multi Pixel Photon Counter) for HEP application

5. MPPC® for medical application
### History of Hamamatsu Si wafer size

<table>
<thead>
<tr>
<th>Wafer size</th>
<th>Production term</th>
</tr>
</thead>
<tbody>
<tr>
<td>φ1.5 inch</td>
<td>1972 ~ 1985</td>
</tr>
<tr>
<td>Φ2 inch</td>
<td>1975 ~ 1986</td>
</tr>
<tr>
<td>Φ3 inch</td>
<td>1983 ~ 1996</td>
</tr>
<tr>
<td>Φ4 inch</td>
<td>1987 ~ 2008</td>
</tr>
<tr>
<td>Φ6 inch</td>
<td>1998 ~</td>
</tr>
<tr>
<td>Φ8 inch</td>
<td>developing</td>
</tr>
</tbody>
</table>
Development of 8inch-PAD detector

6inch-PAD detector
- 12 Polygon shape chip
- 109 x Hexagonal PADs + α

8inch-PAD detector
- Hexagonal shape chip
- 217 x Hexagonal PADs + α
Development of 8inch-PAD detector

Our 1st Proto-type
(target for CMS-HGCAL HL-LHC)

- Size : 8 inch
- Type : N+ in p
  (P-substrate and N-PAD)
- Thickness : 3 types
  • Active 300μm, Physical 300μm
  • Active 200μm, Physical 200μm
  • Active 120μm, Physical 300μm

- Size of PAD : ~ 1cm²
- Number of Hexagonal PAD : 217ch
Result-1
Guard-Ring I-V of Main Sensor

- **300μm and 200μm type**
  - 1000V voltage tolerance, but higher dark current compared to 120μm-type or conventional 6inch.

- **120μm type**
  - 1000V voltage tolerance and low dark current.
We measured IV curve of every channels with surrounded channels GND.

---

**Champion data**

**300μm type**

Channel-IV (300μm type No3 even)

---

**200μm type**

Channel-IV (200μm type No14 even)

---

**120μm type**

Channel-IV (120μm type No2 even)

Some specific chs have higher dark. (→We almost know the cause)

---

- **300μm and 200μm type**
  
  1000V voltage tolerance, but higher dark current.

- **120μm type**
  
  High dark channel (9ch)
Result-3

C-V curve of Mini Diode

- We measured CV curve of Mini Diode and estimated the full depletion voltage.

![Graph showing CV curve of Mini Diode with different depletion voltages for different thicknesses: 300μm type (~280V), 200μm type (~130V), 120μm type (~30V).]
Future prospect of 8inch wafer production

**ODC-type**: PAD-detector, PIXEL
- Development stage ~2019
- Will be available 2020～

**OAC-type**: AC coupled SSD
- Development stage 2020～2022
- Will be available 2023～
1. SSD (Silicon Strip Detector) for tracker of many HEP experiments

2. Development of large area PAD detector

3. APD (Avalanche Photo Diode) for LHC-CMS

4. MPPC® (Multi Pixel Photon Counter) for HEP application

5. MPPC® for medical application
About 130,000 pieces of APD are used for CMS-ECAL

PbWO$_4$ crystal

65,000pcs

Blue light

proton

particle

proton

APD

130,000pcs

Signal

S8148

---

**Spec. (Ta = 25℃)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>STD No</th>
<th>S8148</th>
</tr>
</thead>
<tbody>
<tr>
<td>active area</td>
<td>5 x 5 mm$^2$</td>
<td></td>
</tr>
<tr>
<td>breakdown voltage (VB)</td>
<td>&gt; 325 V</td>
<td></td>
</tr>
<tr>
<td>Operating Voltage (VR)</td>
<td>300 – 450 V</td>
<td></td>
</tr>
<tr>
<td>Difference VB–VR</td>
<td>&gt; 25 V</td>
<td></td>
</tr>
<tr>
<td>Dark current at VR</td>
<td>&lt; 50 nA</td>
<td></td>
</tr>
<tr>
<td>Capacitance at VR</td>
<td>65 – 85 pF</td>
<td></td>
</tr>
<tr>
<td>Quantum efficiency at VR, 430nm</td>
<td>75 ± 5%</td>
<td></td>
</tr>
<tr>
<td>Passivation layer</td>
<td>SiN</td>
<td></td>
</tr>
<tr>
<td>Protective coating</td>
<td>Epoxy Resin</td>
<td></td>
</tr>
</tbody>
</table>
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

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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: ~40V
- High gain: $10^5$ to $10^6$
- Excellent timing resolution
- Insensitive to magnetic fields
- Simple readout circuit operation

Output is summation of all pixel output

\[
Q_{out} = N_{fired} \times C_{\text{pixel}} \times (V_{op} - V_{BR})
\]

\[
N_{fired} = PDE \times N_{\text{photon}}
\]
History of MPPC®s

- **2007**: 1st generation (S10362 series) w/ Low afterpulse
- **2013**: 2nd generation (S1257x series) w/ High Fill factor
- **2015**: 3rd generation (S1336x series) w/ Low afterpulse
- **2017**: New 4th generation (S1416x series) Low Operation voltage

Noise vs. Sensitivity (PDE)
### Characteristics comparison of PD, APD, MPPC and PMT

<table>
<thead>
<tr>
<th></th>
<th>PD</th>
<th>APD</th>
<th>MPPC</th>
<th>PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain</strong></td>
<td>1</td>
<td>$10^2$</td>
<td>$10^5 - 10^6$</td>
<td>$10^5 - 10^7$</td>
</tr>
<tr>
<td><strong>Operation voltage</strong></td>
<td>5 V</td>
<td>100 – 500 V</td>
<td>~40 V</td>
<td>800 – 1000 V</td>
</tr>
<tr>
<td><strong>Large area</strong></td>
<td>No</td>
<td>No</td>
<td>Scalable</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Readout circuit</strong></td>
<td>Complex</td>
<td>Complex</td>
<td>Simple</td>
<td>Simple</td>
</tr>
<tr>
<td><strong>Detection efficiency</strong></td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>Middle</td>
</tr>
<tr>
<td><strong>Noise</strong></td>
<td>Low</td>
<td>Middle</td>
<td>Middle</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Timing reso.</strong></td>
<td>-</td>
<td>-</td>
<td>High</td>
<td>Middle</td>
</tr>
<tr>
<td><strong>Energy reso.</strong></td>
<td>High</td>
<td>Middle</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td><strong>Ambient light resist.</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Magnetic resist</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Compact</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>
MPPC® for T2K Experiment (2008)

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

S10362-13-050C
Installed 56kpcs.

(Provided from Kyoto University)
MPPC® for LHCb SciFi Tracker

Required properties
- Coupled with SciFi matrix
- 64x2ch fine pitch MPPC® array
- Sensitive area: 0.23x1.5mm p0.25mm
- 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

- VUV-MPPC has VUV-sensitivity down to 120nm.
- New developed VUV-MPPC (4th generation: VUV4) is improve photo detection efficiency, which is much higher in comparison with previous VUV-MPPC (VUV3).
- Optical cross-talk is still suppressed by the inter-pixel trench structure.
- VUV4-MPPC achieved improvement of Signal-Noise ratio.
Ultralow-RI Package for physics

ref) K. Yamamoto, et al., ICHEP 2016, ID: 450

For indirect detection (1mm SQ.)  For direct detection (6mm SQ.)

Package type:
- Plastic mold (for indirect detection)
- Pure ceramic (for direct detection)

RI level:
- All radioactive nuclides has not been quantified in on-ground measurement at HPK.
- High precision RI measurements are ongoing with some customers.
MPPC® for MEG II

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)
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MPPC® for PET

APDs or MPPCs arranged around 360° detect pair annihilation gamma-rays to capture the target position such as cancer tissue. APDs and MPPCs can be used with MRI because they are not affected by magnetic fields. In addition, MPPCs are useful for TOF-PET because they have good timing resolution.
MPPC® for scintillation

S14160 series: 3x3, 4x4, 6x6 mm²

Low Break down voltage type. S14161 series (1x1 inch array)

- **Overview**
  
  S14160/S14161 series achieve higher PDE and lower operation voltage than other MPPC to adapt for PET and radiation monitor application.
  
  HWB type achieve small dead space in active area with HWB (Hole Wire Bonding) technology (Patent pending). And the gap from active area edge to package edge is only 0.1mm. This package realizes the 4-side tileable arrangement.

- **Features**
  
  - Higher PDE (50% at λp, VBR+2.7V)
  - Lower voltage (VBR=37V Typ.) operation
  - Small active area dead space
  - Low after pulse and cross-talk
  - High gain: $10^5 \sim 10^6$

- **Application**
  
  - PET
  - Radiation monitor
Characteristics of S14160 series
HPK MPPC® PET module

- **Lutetium scintillator**
  - Low cost
  - (mass production zone)

- **ASIC**
  - Low cost
  - (manufacturing under mass production stage)

- **MPPC:**
  - best type for PET-OEM
  - Best selected MPPC for PET
  - cost down
  - **S14161 Series**

- All components are suitable for PET application
- Big advantage for performance and cost
Summary

1. The history of Hamamatsu SSD is more than 30 years, and SSDs have been used for many HEP experiments.

2. As a new development, we started developing 8-inch PAD detector, and we have obtained several trial results. First we proceed with DC-type, and after that also plan to AC-type.

3. We have developed and delivered APDs and MPPC®s for HEP experiments as well as SSDs.

4. MPPC®’s various characteristics for example sensitivity, noise, after pulse have been improved.

5. MPPC® is widely used in medial fields like PET, in addition to HEP experiments.
Closing

- At this Hiroshima Symposium, I will participate fully 12/11～15.
- We also exhibit Hamamatsu booth during the symposium.
- If you have any interests or, please feel free to speak to me!

Thank you for your attention.
jp.hamamatsu.com