History and Current Status of Hamamatsu Si detectors for High Energy Physics Experiment

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HAMAMATSU PHOTONICS K.K.

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HAMAMATSU PHOTONICS K.K.
Solid State Division
Outline

1. Development and production history of Hamamatsu SSD (Silicon Strip Detector)
2. Our technology for SSD
3. SSD and APD(Avalanche Photo Diode) for LHC
4. Development and characteristic of MPPC® (Multi Pixel Photon Counter)
5. MPPC® for HEP application
Hamamatsu Si detectors for HEP

**Direct detector**
- Silicon Strip Detector (SSD)
- Silicon Pixel Detector

**Photo detector**
- Silicon Photo Diode (PD)
- Silicon Avalanche Diode (APD)
- Multi Pixel Photon Counter (MPPC®)
Development and Production History of SSDs at Hamamatsu

**1980**

- **1984 ~** SSSD R&D
  - 2inch ⇒ 3inch

**1990**

- **1987 ~**
  - SSSD production on 4inch
  - MarkII, DELPHI, ZEUS, ATLAS, etc

**2000**

- **1992 ~**
  - DSSD production on 4inch
  - DELPHI, CLEOII, Belle, CDF, etc

**2010**

- **1998 ~**
  - SSD production on 6inch
  - GLAST, CMS, etc

- **1995 ~**
  - N in N on 4inch
  - ATLAS prot, LHCb prot

- **1992 ~**
  - DSSD R&D on 3inch

- **1989 ~**
  - DSSD R&D on 3inch

- **2009 ~**
  - DSSD on 6inch
  - prot, S-Belle
# 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>
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</thead>
<tbody>
<tr>
<td>MARK II</td>
<td>DC-SSSD 3type</td>
<td>3chip/4inch</td>
<td>44</td>
<td>1987</td>
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<tr>
<td>CLEO II</td>
<td>AC-DSSD 3type</td>
<td>1chip/4inch</td>
<td>122</td>
<td>1993～1994</td>
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<tr>
<td></td>
<td>Pside: punch-through, Nside: poly-Si &amp; DML</td>
<td>2chip/4inch</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELPHI</td>
<td>AC-DSSD 2type</td>
<td>2chip/4inch</td>
<td>130</td>
<td>1993～1994</td>
</tr>
<tr>
<td></td>
<td>both-side: poly-Si, Nside: DML</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DELPHI upgrade</td>
<td>AC-SSSD, FOXFET</td>
<td>2chip/4inch</td>
<td>330</td>
<td>1994</td>
</tr>
<tr>
<td>NOMAD</td>
<td>AC-SSSD, FOXFET</td>
<td>2chip/4inch</td>
<td>650</td>
<td>1996～1997</td>
</tr>
<tr>
<td>CLEO III</td>
<td>DC-SSSD, Psde: DML</td>
<td>2chip/4inch</td>
<td>550</td>
<td>1997～1999</td>
</tr>
<tr>
<td>CDF-SVX</td>
<td>AC-DSSD 3type</td>
<td>1chip/4inch</td>
<td>360</td>
<td>1997～1999</td>
</tr>
<tr>
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<td>both-side: poly-Si, Nside: DML</td>
<td>2chip/4inch</td>
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<td>CDF-ISL</td>
<td>AC-DSSD</td>
<td>1chip/4inch</td>
<td>550</td>
<td>1998～1999</td>
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<td>both-side: poly-Si, Psde: stereo</td>
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<td>PAMELA</td>
<td>AC-DSSD</td>
<td>2chip/4inch</td>
<td>60</td>
<td>1997</td>
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<td>Pside: punch-through, Nside: poly-Si &amp; DML</td>
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<tr>
<td>KEK-B(BELLE)</td>
<td>AC-DSSD</td>
<td>2chip/4inch</td>
<td>180</td>
<td>1998</td>
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<td>both-side: poly-Si, Nside: DML</td>
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<td>ZEUS</td>
<td>AC-SSSD 3type, poly-Si</td>
<td>1chip/4inch</td>
<td>950</td>
<td>1999</td>
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</table>
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<th>period</th>
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</thead>
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<tr>
<td>AGILE</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>500</td>
<td>2000</td>
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<td>PAMELA</td>
<td>DC-SSSD</td>
<td>1chip/6inch</td>
<td>300</td>
<td>2000</td>
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<td>BELLE up grade</td>
<td>AC-DSSD, both-side: poly-Si</td>
<td>2chip/4inch</td>
<td>250</td>
<td>2000~2002</td>
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<tr>
<td>ATLAS</td>
<td>AC-SSSD 6type, poly-Si</td>
<td>1chip/4inch</td>
<td>15500</td>
<td>2001~2003</td>
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<td>GLAST</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>11500</td>
<td>2001~2003</td>
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<tr>
<td>CMS</td>
<td>AC-SSSD 14type, poly-Si</td>
<td>1chip/6inch</td>
<td>24000</td>
<td>2003~2006</td>
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<tr>
<td>LHC-b</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>560</td>
<td>2005~2006</td>
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<tr>
<td>ALICE</td>
<td>AC-SSSD 2type, poly-Si</td>
<td>1chip/6inch</td>
<td>106</td>
<td>2005~2006</td>
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<td>Phenix</td>
<td>Strippixel, DML</td>
<td>3chip/6inch</td>
<td>600</td>
<td>2007</td>
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<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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<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>
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<tr>
<td>HALL-B</td>
<td>AC-SSSD (stereo) 3type, poly-Si</td>
<td>1chip/6inch</td>
<td>434</td>
<td>2012</td>
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<tr>
<td>BELLE-II</td>
<td>AC-DSSD, 2type, Poly-Si</td>
<td>1chip/6inch</td>
<td>265</td>
<td>2011~2014</td>
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<tr>
<td>DAMPE</td>
<td>AC-SSSD, poly-Si</td>
<td>1chip/6inch</td>
<td>768</td>
<td>2014</td>
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</table>
1. Development and production history of Hamamatsu SSD (Silicon Strip Detector)

2. Our technology for SSDs

3. SSD and APD (Avalanche Photo Diode) for LHC

4. Development and characteristic of MPPC® (Multi Pixel Photon Counter)

5. MPPC® for HEP application
**Design of Photo masks**

CAD soft on PC is mainly used for Si detectors. Each coordinates of figures can be inputted by macro program made by EXCEL etc.

Photo-mask design of complicated shape like any angle or rounded strips pattern are acceptable.
Wafer process

Nearly 10,000 of 6 inch wafers are processed per month. We have process lines for PD, Bipolar photo IC, CCD, C-MOS and MEMS Devices

For SSDs

2,000 wafers per month were processed for LHC mass production. Available type: SSSD or DSSD, AC or DC-coupling, Double-metal Available thickness: 150 to 650um for SSSD, 320 and 500um for DSSD

- Oxidation
- Photolithography
- Ion Implantation
- Poly-Si process
- Metal Evaporation
- Passivation
**Wafer probing**

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**Example of Probing for SSDs**

1) Lot check using TEG
   - implant resistance
   - poly-Si resistance
   - Flat-band voltage
   - capacitance of Cc
   - IV & CV of Monitor PD

2) IV curve of main chips
   Chose good wafers

3) Put chip serial number
   Binary notation at Scratch PADs on chip
   ( Dicing )

4) AC & DC check of strips

5) IV & CV curve of main chips
Double sided Wafer probing

Restriction
1) Wafer shape
2) Larger than 80um pad size

Example of Probing
1) DC check of N strips for DSSD
   - require P side biasing
2) TSV-MPPC with back side PADs
   - require front side illumination

Wafer peripheral edge is clamped
Stealth Dicing Technology

We also have **Stealth dicer** in addition to the traditional **blade dicer**. Polygon shape, chips of different size can be cut without chipping.

Baby detectors, Test structures, Mos diodes, Monitor diodes can be cut by stealth dicer in one set and one program.

[from Hamamatsu homepage]
Failure Analysis

Easy to know where is weak points and lower break down voltage

- Design of photomask mainly for guard rings and edge of stripes
- Analysis of popcorn noise by micro plasma
- Contamination and defects analysis made by process and handling
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ATLAS - SSD

provided from CERN experiment groups
ATLAS-SSD (S8536 series)

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

1 Sensor on 4 inch wafer

6 type of S8536 series
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

PRESHEOWER
Armenia, Belarus, CERN, Greece, India, Russia, Taiwan (*), Uzbekistan

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, * Only through industrial contracts
Endcap: Belarus, Bulgaria, China, Korea, Pakistan, Russia, USA

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
Vfd and Leakage current for CMS-thick type SSDs

Vfd distribution is due to the resistance variation of the wafer material.
Dark current distribution is good and much less than specification.

Vfd distribution:
- Total: 7310
- Min: 90V
- Max: 280V
- Ave: 203V
- $\sigma$: 29V

Dark current distribution:
- Total: 7310
- Min: 238nA
- Max: 2367nA
- Ave: 430nA
- $\sigma$: 134nA
Bad channel rate for CMS-SSDs

More than 95% of detector are perfect with no bad channels. The average of bad channel rate is around 0.01%. Short of Cc, Open of strip implant, short of AC AL are main factor of bad channel.
CMS - APD

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provided from CERN experiment groups

Kazuhisa. Yamamura / 2015/09/25-29 10th HSTD @ Xi’an, China
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
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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: \(\sim 70\) V
- 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

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

\[ N_{fired} = PDE \times N_{photon} \]
Latest Development of MPPC®s

Noise

2007
1st generation (S10362 series)

2013
2nd generation (S1257x series)

w/ Low after pulse

2014
Latest (S1308x series)

w/ Low crosstalk

2015
Newest (S13360 series)

w/ High Fill factor

Sensitivity (PDE)
Low After Pulses

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.
Crosstalk comparison

3x3 mm² 50μm pitch

Overvoltage (V)

Cross Talk (%)

1st: S10362
2nd: S12572
NEW: S13360

3rd generation MPPC have drastically improved crosstalk and can be used at higher overvoltage
As generation increases, pulse height distribution is improved. Third generation is excellent photon-counting capability.
Dynamic range of MPPC®

MPPC® maximum output is determined by:
• Large number of MPPC® pixels
• Short recovery time

Merit and Demerit of small pixel

Merit⇒ Large number of pixels, Short recovery time
Demerit⇒ 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

Dynamic range by readout method of MPPC®

Photosensitive area : 3x3mm
Dynamic range by readout method of MPPC®

Photosensitive area: 3x3mm

- 50um pitch
- 10um pitch

Analog Mode

Difference by PDE

Difference by pixel number & recovery time

Difference by noise & PDE

Counting mode

Incident photons (cps)

Output (cps)
MPPC® array with TSV(Through Si Via)

3-side buttable

4x4ch monolithic array with wire bonding S11828 series

4-side buttable

4x4ch discrete array with TSV S13361-3050 series

3x3mm Single 50mmp with TSV

The TSV process requires small non-sensitive area (200mm sq.).

This area is corresponding to 0.44% of total active area, and it is hardly affected to the PDE (photon detection efficiency).
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# Characteristics of MPPC and PMT

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>MPPC</th>
<th>PMT</th>
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<tbody>
<tr>
<td><strong>GAIN</strong></td>
<td>$10^5 \sim 10^6$</td>
<td>$10^5 \sim 10^7$</td>
</tr>
<tr>
<td><strong>Operation Voltage</strong></td>
<td>60~80</td>
<td>~1000</td>
</tr>
<tr>
<td><strong>Active area</strong></td>
<td>10 mm$^2$</td>
<td>$\geq 10000$ mm$^2$</td>
</tr>
<tr>
<td><strong>Dark count</strong></td>
<td>$\triangle$</td>
<td>$\bigcirc$</td>
</tr>
<tr>
<td><strong>Detection effi.</strong></td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
</tr>
<tr>
<td><strong>Timing reso.</strong></td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
</tr>
<tr>
<td><strong>Energy reso.</strong></td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
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<tr>
<td><strong>Compact</strong></td>
<td>$\bigcirc$</td>
<td>$\bigcirc$</td>
</tr>
<tr>
<td><strong>Magnetic resist.</strong></td>
<td>$\bigcirc$ (7 T)</td>
<td>$\times$ (1.5 T)</td>
</tr>
</tbody>
</table>
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 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
- Sensitive area: 6mm 4ch Hexagonal

**Cherenkov Telescope Array**

![Image of Cherenkov Telescope Array]

- SST × (32 + 8)
  - D = 4 - 6 m
  - FOV = 10°
  - E = 1 TeV – 100 TeV
- MST × (23 + 17)
  - D = 10 - 12 m
  - FOV = 6° - 8°
  - E = 100 GeV – 10 TeV
- LST × (4 + 4)
  - D = 33 m
  - FOV = 4° - 5°
  - E = 20 GeV – 1 TeV

**λ > 290nm**

- Cherenkov at FP, coll. eff.: 21%
- Night sky background at FP, coll. eff.: 14%
- Photon detection efficiency
- Scaled quantum efficiency

**S12516**

- Light guides

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**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.

(Pictures from Tokyo University)

- **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)
Summary

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

2. We have enough capability to design, process, and inspection of Si detectors for HEP.

3. We have developed and delivered SSDs and APDs for LHC-ATLAS and CMS experiment.

4. MPPC® characteristics for example after-pulses, cross-talk, pulse height distribution and dynamic range have been improved.

5. T2K experiment adopted MPPC®s and is using 56,000 pieces of 1.3x1.3mm-MPPCs. MPPC® will be expected and evaluated for HEP experiments.
Closing

We Hamamatsu are proud that our Si-detectors are used for many physical experiments. We continually make efforts to provide a better sensor, and contributes to the development of physics.

Thank you for your attention!