Irradiation and Testbeam of KEK/HPK Planar p-type Pixel Modules for HL-LHC

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On behalf of ATLAS-Japan silicon group,
Hamamatsu Photonics K.K.
and ATLAS PPS collaboration

2nd Sep, 2014
Outline

• Introduction
  – HL-HLC and Planer type Pixel sensor
  – Issue of inefficiency spot at pixel boundary.
  – New design to solve this issue

• Testing new design pixel detector
  – Irradiation facility in Japan (CYRIC)
  – Testbeam at CERN and DESY

• Result and Conclusion
Introduction

- **High Luminosity LHC (HL-LHC)**
  - Start around 2025 - with new crab cavity in the interaction region.
  - Target: $\sqrt{s}=14\text{TeV}$ $L=5\times10^{34} \int Ldt=3000\text{fb}^{-1}$
  - Physics program focus the precise measurement of the Higgs coupling (e.g. $Y_\tau$, $Y_b$ and $\lambda_{HHH}$) and BSM searches.

- **Tracking detector is key element**
  - To keep B/τ-tagging performance up to $\mu=200$ pileup in an event.
  - Mitigation for the pileup effect for MET calculation can be done by tracking from primary vertex.

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B-tagging performance for each pileup cond. (keep the same efficiency)

High efficiency and radiation tolerant detector is important

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Development of Planer pixel module

- Planer pixel module (Outer Pixel layer(s))
  - FE-I4 read out chip on the \textbf{n}^+\text{-in-}\text{p}^+\text{ type} sensor.
  - Pixel size: \textbf{50x250}\textmu m, thickness: \textbf{150}\textmu m
  - Time-over-threshold (ToT) readout using 15x25ns clock.
- Expected radiation fluence in 3000\text{fb}^{-1} is \sim 1\times10^{15} \text{ 1MeV neq/cm}^2
  - test 3-5x10^{15} fluence to confirm radiation-tolerance.
Issue: Inefficiency at pixel boundary

- In results of CERN 2012 testbeam, we observed inefficiency/charge loss at pixel boundary region after irradiation.
- The region is correspond to the bias-rail and poly-si resister structures.

Pixel Efficiency map

After p+ irradiation (1e16 neq)

Overall efficiency ~97% is caused by inefficiency at pixel boundary region.

Charge loss (~10%) under the poly-si resister

Efficiency loss under bias-rail.
Possible solution of new structure

• Original Structure

• Type 10

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Irradiation
Irradiation @ CYRIC

- CYRIC@Tohoku Univ. is a irradiation facility with 70MeV proton beam (~1μA).
  - This allows 2-3 pixel module with back Al plain at the same time (3% E loss/pixel).
  - Operated at -5°C temperature with dry N₂ gas. → trying to make lower Temp.

- Programmable X-Y stage and “push-pull” mechanism are implemented to the machine.
  - choose one or a few target samples in max 15 pre-installed samples.

- Scanning over full pixel range during irradiation.
Fluence calculation by Al dosimetry

• 1x1cm$^2$ Al foils are put on the irradiation samples.
• Produced $^{24}$Na are measured by Ge Photon counter.
• Proton dose(D) is obtained as follows:

\[
D \ [\text{neq/cm}^2] = \frac{N_{^{24}Na}}{N_{target} \times \sigma_{p-Al}} \times \frac{\tau \cdot t}{1 - e^{-\tau \cdot t}} \times 0.7
\]

- $N_{^{24}Na}$ : Number of produced $^{24}$Na
- $N_{target}$ : Number of target Al atoms
- $\sigma_{p-Al}$ : proton – Al cross section [cm$^2$]
- $\tau$ : $^{24}$Na decay constant [1/s]
- $t$ : irradiation duration [s]

Difference of target and actual fluence is within 10% level.
Testbeam
Testbeam @ CERN and DESY

- Performed testbeam at CERN in 2012 and at DESY 2013-2014.
  - **CERN H6 beamline**: 120GeV π+ beam (Test traditional structure)
  - **DESY T22 beamline**: 4 GeV e+ beam (Test new structure)
- 6 Telescope plain (FE: Mimosa26, 18.4x18.4μm²) and Detector-Under-Testing (DUT) are installed.
  - 4 DUTs at CERN and 2 DUTs at DESY.
- For DESY testbeam, to reduce multiple scattering effect Telescope positions are optimized.

** Typical DESY testbeam setup **

<table>
<thead>
<tr>
<th>telescope</th>
<th>DUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>
Reconstruction and pointing resolution

- EUTelescope based on ILCSoft/Marlin framework is used for alignment and reconstruction.
- Pointing resolution by the telescope plains interpolating to the DUT position are quantified as fitting the shoulder of residual distribution by error function.
  - 23\(\mu\)m resolution for DESY data by multiple scattering.

\[ \sigma_{\text{CERN}} = 4.5 \pm 0.1 \]
\[ \sigma_{\text{DESY}} = 23.2 \pm 0.2 \]

23\(\mu\)m resolution is enough to see structure for long direction. But may be difficult to see short direction.
Results
Overall Efficiency and ToT

Type 10
Sensor: 150 µm
Dose: 4 x 10^{15} n_{eq}
Th: 1800e, ToT: 5 @5ke

Type 13
Sensor: 320 µm
Dose: 3 x 10^{15} n_{eq}
Th: 2600e, ToT: 7 @10ke

Type 19
Sensor: 320 µm
Dose: 3 x 10^{15} n_{eq}
Th: 1800e, ToT: 7 @10ke

Bias Voltage vs Efficiency

~78%
no reference plane
(unknown abs. effi)

Bias Voltage vs ToT

2 cluster hit
1 cluster hit

5ke

10ke

~99%

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Efficiency Pixel Map

**Type 10**
Sensor: 150 μm Dose: $4 \times 10^{15} \text{n_{eq}}$
Th: 1800e, ToT: 5 @5ke

**Type 13**
Sensor: 320 μm Dose: $3 \times 10^{15} \text{n_{eq}}$
Th: 2600e, ToT: 7 @10ke

**Type 19**
Sensor: 320 μm Dose: $3 \times 10^{15} \text{n_{eq}}$
Th: 1800e, ToT: 7 @10ke
**Efficiency Pixel Map**

<table>
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<tr>
<th>Type</th>
<th>Sensor:</th>
<th>Dose:</th>
<th>Th:</th>
<th>ToT:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 10</td>
<td>150 μm</td>
<td>$4 \times 10^{15}$ neq</td>
<td>1800e</td>
<td>5 @5ke</td>
</tr>
<tr>
<td>Type 13</td>
<td>320 μm</td>
<td>$3 \times 10^{15}$ neq</td>
<td>2600e</td>
<td>7 @10ke</td>
</tr>
<tr>
<td>Type 19</td>
<td>320 μm</td>
<td>$3 \times 10^{15}$ neq</td>
<td>1800e</td>
<td>7 @5ke</td>
</tr>
</tbody>
</table>

No large Efficiency loss are observed in >400V

**Projection to X (long axis)**

- 200V
- 400V

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Definition of Efficiency loss

Since pointing resolution is different between CERN and DESY testbeam, to quantify the effect of Efficiency loss, area of inefficiency is used by fitting Gaussian distribution.

Eff. loss per pixel := \( \frac{S}{1.0 \times 500 \, \mu m} \)

E.g.

- 5\% region in 2 pixel length have 50\% efficiency
  \[ \rightarrow \text{Eff. Loss per pixel} = 0.025 \]
Thickness and Fluence Correction

- Thickness and fluence are not identical for each Type of samples.
  - Type 13 & 19 sensors are 320μm thick.
  - The others are 150μm thick.
  - Fluence are also different 3-5x10^{15}

- To compare the efficiency drop for the different thickness and Fluence:
  - Efficiency loss of bump-side of Type 13 should agree with one of Type 10.
  - Approximately, fit by an error function and calculate transfer function.
  - Apply the transfer function to the Bias-rail side.
Results (150um, 5x10^{15} neq/cm^2 Equivalent)

Traditional Structure
Bias rail(Al)+ Resister(PolySi)

Type 13
Bias rail+Resister(PolySi)
Wide p-stop under bias rail
Bias res. is inside of electrode

Type 19
Ideal situation.
No bias rail and resister.

Type 10
Shifted Bias rail position.
Bias res. is inside of electrode

Type 10 is the best option
→ Almost similar to ideal case
Conclusion and Plan

• Irradiation facility, CYRIC, and irradiation technique have been well established.
  – Fluence difference from the target value is within 10% level.
  – **Plan**: Temperature control system is improved for the next irradiation (Sep 15-18, 2014)

• New pixel structures are well tested by testbeam.
  – Largely improved efficiency around pixel boundary.
  – Especially offset of bias-rail helps.
  – **Plan**: Full optimization of structure and material for the bias-rail (Al or Poly-Si). Comparison on the same thickness and fluence (i.e. without correction). Take HV scan upto higher Voltage (1000V).
Contributors

• ATLAS-Japan Silicon Group

• Hamamatsu Photonics K.K

• ATLAS PPS collaboration
Backup
### New Structure

<table>
<thead>
<tr>
<th>Design</th>
<th>Structure Image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original Structure</strong>&lt;br&gt;Bias rail (Al)&lt;br&gt;Bias resister (PolySi)</td>
<td>Traditional structure with bias rail and resister at inter pixel region.</td>
</tr>
<tr>
<td><strong>Type 10</strong>&lt;br&gt;Bias rail (PolySi)&lt;br&gt;Bias resister (PolySi)</td>
<td>To avoid “efficiency drop” at under bias rail and resister, shift the bias rail and resister position to inside of pixel electrode.</td>
</tr>
<tr>
<td><strong>Type 13</strong>&lt;br&gt;Bias rail (PolySi)&lt;br&gt;Bias resister (PolySi)</td>
<td>Bias resister is the same as type 10 but keep bias rail at traditional position and <strong>made p-stop wider.</strong></td>
</tr>
<tr>
<td><strong>Type 19</strong>&lt;br&gt;Bias rail (PolySi)&lt;br&gt;Bias resister (PolySi)</td>
<td>To test <strong>ideal situation</strong>, remove all bias rail and resister structure.&lt;br&gt;* Note : QA is not possible at sensor level. So this is just for test.</td>
</tr>
</tbody>
</table>
Our default testing system (USBpix)

- Using USBpix DAQ system to check:
  - Tuning of FE-I4
  - $^{90}\text{Sr}$ Source scan to find disconnected bump. (self trigger)
  - Thermal cycling is operated $[-40,40]$ °C with dry N$_2$ flow.

- USBpix systems are used for most of testbeams in last a few years.
  - In principle, it’s working without major issue.
  - Used RCE system in SLAC testbeam with more stable DAQ.
Irradiation facility: CYRIC

- CYRIC @ Tohoku Univ.
  - Beam energy is 70 MeV which allows to irradiate 3 modules at once.
    (Karlsruhe is 25.3 MeV)
  - With intelligent irrad Box
  - Fluence are evaluated by Al dosimetry ($^{24}$Na).

Next Irradiation is mid September

<table>
<thead>
<tr>
<th>CYRIC (Jan 2014)</th>
<th>P+ Energy</th>
<th>70 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Current</td>
<td>10-1000 nA</td>
<td></td>
</tr>
<tr>
<td>Time</td>
<td>6h @ 600nA for 3x10^{15} neq/cm²</td>
<td></td>
</tr>
<tr>
<td>Scan speed</td>
<td>20 mm/s</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>-5-20°C (Chiller+dry N₂)</td>
<td></td>
</tr>
</tbody>
</table>
Efficiency drop issue and new structure I

• In the past testbeam we could find small efficiency drop after irradiation (99.7→97% at Full depletion voltage).
• The drop is not uniformly over the pixel area but quite specific area : inter pixel region.
  – Especially the region on the bias rail and bias resister structures.
• Goal : To understand this efficiency drop and find solution.

Typical efficiency map after irradiation

Hit Efficiency vs Bias Voltage

Non-irrad ~ 99.7%
Irrad ~ 97%

Bias rail
P-stop
Bias resister

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