Development and Study of the Multi Pixel Photon Counter

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for the KEK Detector Technology Project / Photon Sensor Group

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KEK Detector Technology Project
Photon Sensor Group
(http://rd.kek.jp/)
(KEK, Kobe, Kyoto, Nagoya, Nara-WU, NDA, Niigata, Shinshu, Tokyo/ICEPP, Tsukuba)


And special thanks to Hamamatsu photonics K.K.
The Multi Pixel Photon Counter (MPPC) - A silicon avalanche photo-diode with multi-pixel structure -

- Each pixel works as a Geiger-mode APD,
- One pixel can count only one photon.
  → need multi-pixel structure for photon counting
- Electric charges from all the fired pixels are summed up and read out as a signal.
- There are 4 different types available:

<table>
<thead>
<tr>
<th># of pixels</th>
<th>Sensor size</th>
<th>Pixel size</th>
<th>Geometrical eff.</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>1x1 mm²</td>
<td>100 μm</td>
<td>~ 0.65</td>
</tr>
<tr>
<td>400</td>
<td></td>
<td>50 μm</td>
<td>~ 0.5</td>
</tr>
<tr>
<td>1600</td>
<td></td>
<td>25 μm</td>
<td>~ 0.25</td>
</tr>
</tbody>
</table>
Excellent Photon Counting Ability

0, 1, 2, 3, 4, 5, 6, 7, . . . photoelectrons!

1600 pixel

MPPC signal (ADC counts)
The MPPC has lots of advantages

<table>
<thead>
<tr>
<th></th>
<th>Photomultiplier</th>
<th>MPPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>~10^6</td>
<td>10^5~10^6</td>
</tr>
<tr>
<td>Photon Detection Eff.</td>
<td>0.1 ~ 0.2</td>
<td>0.2 (1600pix.) ~ 0.5 (100pix.)</td>
</tr>
<tr>
<td>Response</td>
<td>fast</td>
<td>fast</td>
</tr>
<tr>
<td>Photon counting</td>
<td>Yes</td>
<td>Great</td>
</tr>
<tr>
<td>Bias voltage</td>
<td>~ 1000 V</td>
<td>~ 80 V</td>
</tr>
<tr>
<td>Size</td>
<td>Small</td>
<td>Compact</td>
</tr>
<tr>
<td>B field</td>
<td>Sensitive</td>
<td>Insensitive</td>
</tr>
<tr>
<td>Cost</td>
<td>Expensive</td>
<td>Not expensive</td>
</tr>
<tr>
<td>Dynamic range</td>
<td>Good</td>
<td>Determined by # of pixels</td>
</tr>
<tr>
<td>Long-term Stability</td>
<td>Good</td>
<td>Unknown</td>
</tr>
<tr>
<td>Robustness</td>
<td>decent</td>
<td>Unknown</td>
</tr>
<tr>
<td>Noise (fake signal by thermions)</td>
<td>Quiet</td>
<td>1 pixel noise exist (order of 100 - 500 kHz)</td>
</tr>
</tbody>
</table>
Fundamental performance

• Gain
• Dark Noise Rate
• Inter-pixel Cross-talk
• Photon Detection Efficiency
• Uniformity in a pixel
Fundamental Performance - Gain

Gain = \frac{C}{e} (V_{bias} - V_0)

- $C$ ... Pixel capacity
- $V_0$ ... Breakdown voltage

$V_0 \propto$ temperature ($\Delta V_0/\Delta T \approx 50 \text{ mV/C}^\circ$)

Larger pixel size results in larger gain.
Variation of $V_0$ and $C$ over 750 MPPCs
(Measured at $15^\circ C$)

- Variation $\sim 0.45$ V
- Variation $< 4\%$

• ~750 pieces of 1600 pixel MPPCs have been tested.
• Device-by-device variation is less than a few %.

→ No need for further selection or categorization on massive use!
    Just need a small tuning of operation voltages.
The dark noise is caused by thermal electrons.

Its rate depends on both over-voltage and temperature.

More number of pixels → smaller active area → fewer noise rate
• Inter-pixel cross-talk is caused by a photon created in an avalanche.
• Probability of the cross-talk has been measured using dark noise rates:

\[ P_{\text{crosstalk}} = \frac{\text{Noise Rate}(\geq 2 \text{ pix.})}{\text{Noise Rate}(\geq 1 \text{ pix.})} \]

• Cross-talk probability is affected by over-voltage, but not affected by temperature.
Fundamental Performance
- Photon Detection Efficiency (P.D.E) -

\[ PDE(MPPC) = Q.E. \times \epsilon_{Geiger} \times \epsilon_{geom} \]

- **Q.E.** (~ 0.9) … Quantum Efficiency
- **\(\epsilon_{Geiger}\)** (~ up to 0.9, depends on bias voltage) … Probability to cause avalanche
- **\(\epsilon_{geom}\)** (0.25 ~ 0.65, depends on pixel size) … Fraction of sensitive region in a sensor

**Measurement of relative P.D.E.**
- Inject same light pulse into both the MPPC and the PMT, and compare light yield measured by both:

\[ \frac{PDE(MPPC)}{PDE(PMT)} \approx 15\% \]

\[ \frac{N_{p.e.}(MPPC)}{N_{p.e.}(PMT)} \]
Fundamental Performance
– Photon Detection Efficiency -

- PDE of the MPPC is x1~2 of the PMT!
- Larger pixel size
  → less dead space
  → larger PDE
- The PDE also depends on over-voltage, and slightly affected by temperature change.
Laser Scan in One Pixel

- Pin-point scan has been done using YAG laser ($\lambda = 532$ nm) with spot size ~ 1 $\mu$m.
- Variation of photon sensitivity and gain in one pixel are evaluated.
- Observed variation is 2 ~ 5 % in a sensitive area for the 100 / 400 / 1600 pixel MPPCs.

1600 pixel Sensitivity

1600 pixel Gain
Practical Applications
Application to High Energy Physics
- Calorimeter for linear collider experiment -

Light yield of scintillator strip (1 x 4.5 x 0.2 cm)
for beta-ray

WLS fiber readout

Direct readout

Light yield
~ 21 p.e.

Light yield
~ 13 p.e.

Light yield (ADC counts)

- The MPPC is feasible for strip-type scintillator calorimeter.
  (size, cost, performance…)
- Dynamic range is the key issue.
- First scintillator-ECAL beam test will start in next week at DESY!
Application to High Energy Physics
- T2K near detectors -

- OffAxis detector
- OnAxis detector

Scintillator + WLS fiber
With MPPC readout

- Need to read out large number of signals from WLS fibers in limited space
  - Used in 0.2 Tesla magnetic field
  - The MPPC is the perfect solution!

- Belle Ring Imaging Cerenkov Detector -

- Aerogel radiators

MPPC array

- Capture Cerenkov ring image for particle ID
- For the ring imaging,
  - Sufficient photon detection efficiency
  - Position resolution (~5 mm) are required for photon sensor.
- MPPC is a powerful candidate for this purpose,
- Larger sensor area (~3x3 mm²) is desired in future development.
The MPPC is still evolving …
Stay tuned for future development!

- **Mar. 2005**
  - 100/400 pixels
  - First sample from Hamamatsu

- **Jan. 2006**
  - 100/400/1600 pixels
  - Larger PDE
  - More pixels

- **2006-2007**
  - 100/400/1600 pixels
  - Commercialized
  - Improved Gain and dark noise
  - Tests of massive use

- **Near future**
  - Improved performance
  - Larger sensor area
  - More pixels

Stay tuned for future development!
Summary

• The MPPC is a promising photon sensor which has many remarkable features.
  – High gain, compact size, low-cost, excellent P.D.E., etc ….

• Extensive R&D of the MPPC is ongoing in KEK DTP group collaborating with Hamamatsu photonics.
  – Study and improvement of basic properties … underway
  – Evaluation of variation over many samples … underway
  – Study radiation hardness (for $\gamma$-ray, neutron) … just started
  – Evaluate robustness and long-term stability … start soon
  – Test magnetic-field tolerance … near future

• Tests for actual use at several high energy physics experiments are also underway.

• Applications in various other fields are being explored.
  – Positron Emission Tomography, etc…

• The improvement of the performance will be continued toward the “Perfect Photon Sensor”!
The KEK Detector Technology Project group will host an international workshop for the future photon sensors. Check the KEKDTP web site:  
http://rd.kek.jp/  
Contact : Takeshi.Nakadaira@kek.jp
Backups
Application to Other Fields

**Positron Emission Tomography (PET)**
... a powerful method to detect cancer activity.
- Capture gamma pair and identify position of the cancer.
- Spatial resolution is greatly improved by finer granularity (~1 mm of crystal block size).
- MPPC is ideal to read out each individual crystal blocks.
MPPCs on sale

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<th>400</th>
<th>1600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pixels</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sensor size</td>
<td>1 x 1 mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nominal Bias Volt.</td>
<td>70 ±10 V</td>
<td>77 ±10 V</td>
<td></td>
</tr>
<tr>
<td>Gain (x 10⁵)</td>
<td>24.0</td>
<td>7.5</td>
<td>2.75</td>
</tr>
<tr>
<td>Noise Rate (kHz)</td>
<td>400</td>
<td>270</td>
<td>100</td>
</tr>
<tr>
<td>Photon Detection Efficiency</td>
<td>65 %</td>
<td>50 %</td>
<td>25 %</td>
</tr>
<tr>
<td>Temperature dependence (ΔV₀/ΔT)</td>
<td></td>
<td></td>
<td>50 mV / °C</td>
</tr>
</tbody>
</table>

(Numbers from HPK catalog)

- Hamamatsu photonics is starting to deliver the MPPC.
- See following page for more information: