“Silicon-based Photomultipliers”

a new generation of photon detector

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Outline

• Introduction
• Operation principle
• Multi-Pixel Photon Counter (MPPC)
  • Performance
  • Future developments
• Summary
Introduction
“Silicon Photo-multiplier”??

- Known in many many names...
  - SiPM
  - MRS-APD
  - SPM
  - MPPM APD
  - AMPD
  - GM-APD
  - MPPC
  - ....

- Reflecting progress in many places in short time.
R&D over the world

CPTA

MEPHI/PULSAR

Dubna/Mikron

SenSL

MPI

ITC-irst

HPK

Some maybe missing..
Why so interesting?

- Many **advantages**:
  - High \((10^5-10^6)\) gain with low voltage (<100V)
  - High photon detection efficiency
  - Compact and robust
  -Insensitive to magnetic fields

- Although as many **possible drawbacks at this moment**:
  - Only small size (typically \(\sim\)mm\(^2\)) available
  - High dark count rate (100kHz-1MHz/mm\(^2\))
  - Optical cross-talk and after-pulse
Example of considered applications

- HEP
  - Neutrino detectors
  - ILC calorimeter/muon detectors
  - Aerogel-RICH for super-B, ....
- Astrophysics
  - Air Cherenkov telescopes, ....
- Medical
  - PET, .....
Example of application:

**T2K near detectors**

(Long baseline ν oscillation experiment from 2009)

- Measure ν properties just after production
- Most of sub-detectors will use plastic scintillators + wavelength-shifting fibers
- Some placed inside magnetic field
- Severe constraint on available space
- Chosen MPPC (Hamamatsu device) as the photo-sensor
- ~60,000 channels in total
- First use in large-scale real exp.
Operation principles
Avalanche Photodiodes (APDs)

- Photon creates e-h pair near surface
- **Avalanche amplification** in reverse-biased region
- **Linear operation** below breakdown voltage ($V_{bd}$): output charge $\propto$ number of e-h pairs $\propto$ number of incident photons
- Typical internal gain: 10-100 (~1000 some case)
Geiger-mode operation of APDs

- Operation **above** the breakdown voltage
- **High internal gain**
- **Binary device**
  - Same amount of charge regardless of number of incident photons
- Discharge may be ‘quenched’ by external register

![Graph showing log(gain) vs. Bias voltage with Geiger mode and Linear mode](image)

- $V_{bd}$
- Linear mode
- Geiger mode

M. Yokoyama @ SLAC AIS, 8/22/2007
Counting Photons with Geiger-mode APDs

- Divide APD into many small pixels.
- Each pixel works independently in Geiger mode.
- Incident photon ‘fires’ an APD pixel but not others.
- Output charge from one pixel: \( Q_{\text{pixel}} = C_{\text{pixel}} \cdot (V_{\text{op}} - V_{\text{bd}}) \)
- \( C_{\text{pixel}} \sim 10 - 100 \text{fF} \) and \( \Delta V \equiv V_{\text{op}} - V_{\text{bd}} \sim 1 - 2 \text{V} \) gives \( Q_{\text{pixel}} \sim 10^5 - 10^6 \text{e} \)
Operation of Multi-pixel Geiger-mode APDs

- All the pixels are connected in parallel
- Taking sum of all pixels, one can know how many pixels are fired \( \propto \) how many photons are incident!
- \( Q = \sum Q_{\text{pixel}} = N \cdot Q_{\text{pixel}} \)
Output from Multi-pixel Geiger-mode APD

Clear separation of 1, 2, 3... photoelectron (p.e.) peaks!
[@ room temperature]
Comparison of photo-sensors

<table>
<thead>
<tr>
<th></th>
<th>PMT</th>
<th>APD</th>
<th><code>SiPM</code></th>
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<tbody>
<tr>
<td><strong>Gain</strong></td>
<td>$10^6-10^7$</td>
<td>~100</td>
<td>$10^5-10^6$</td>
</tr>
<tr>
<td><strong>Operation voltage (V)</strong></td>
<td>1-2k</td>
<td>300-500</td>
<td>&lt;100</td>
</tr>
<tr>
<td><strong>Active area</strong></td>
<td>~&gt;100cm$^2$</td>
<td>~10mm$^2$</td>
<td>~1mm$^2$</td>
</tr>
<tr>
<td><strong>Dark count (Hz)</strong></td>
<td>&lt;1k</td>
<td>0.1-1M</td>
<td></td>
</tr>
<tr>
<td><strong>Photon detection efficiency (blue-green)</strong></td>
<td>~15%</td>
<td>75-80%</td>
<td>20-50%</td>
</tr>
<tr>
<td><strong>Magnetic field</strong></td>
<td>x</td>
<td>o</td>
<td>o</td>
</tr>
</tbody>
</table>
Multi-Pixel Photon Counters (MPPC)

Menlo Park Presbyterian Church →
www.mppc.org
MPPC by Hamamatsu

- Structure based on CMS-APD
- Currently on catalogue:
  - 1x1 mm² active area
  - 100/50/25 µm pixel pitch
  - Metal or ceramic package
- In future:
  - Larger area: 3x3 mm² (5x5 mm²)
  - Larger pixel pitch
  - More variations of package
## Specifications by Hamamatsu

### Electrical and optical characteristics (Ta = 25°C)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1600</th>
<th>400</th>
<th>100</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Chip size</td>
<td>1.5 x 1.5</td>
<td></td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Effective active area</td>
<td>1 x 1</td>
<td></td>
<td></td>
<td>mm</td>
</tr>
<tr>
<td>Number of pixels</td>
<td>1600</td>
<td>400</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Pixel size</td>
<td>25 x 25</td>
<td>50 x 50</td>
<td>100 x 100</td>
<td>um</td>
</tr>
<tr>
<td>Geometric efficiency</td>
<td>30.8</td>
<td>61.5</td>
<td>78.5</td>
<td>%</td>
</tr>
<tr>
<td>Sensitivity</td>
<td></td>
<td></td>
<td></td>
<td>nm</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td></td>
<td></td>
<td></td>
<td>%</td>
</tr>
<tr>
<td>PDE</td>
<td>25</td>
<td>50</td>
<td>65</td>
<td>%</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>77±10</td>
<td>70±10</td>
<td>70±10</td>
<td>V</td>
</tr>
<tr>
<td>Gain</td>
<td>2.75E+05</td>
<td>7.50E+05</td>
<td>2.40E+06</td>
<td>-</td>
</tr>
<tr>
<td>Dark count</td>
<td>100</td>
<td>270</td>
<td>400</td>
<td>Kcps</td>
</tr>
<tr>
<td>Terminal capacitance</td>
<td>35</td>
<td></td>
<td></td>
<td>pF</td>
</tr>
<tr>
<td>Time resolution (FWHM)</td>
<td>250</td>
<td>220</td>
<td>250</td>
<td>ps</td>
</tr>
<tr>
<td>Temp coefficient of bias voltage</td>
<td>50</td>
<td></td>
<td></td>
<td>mV/°C</td>
</tr>
</tbody>
</table>

The last letter of each product number indicates which type of package is used. (U: Can, C: Ceramic)

The figures in PDE (Photon Detection Efficiency) include cross-talk and after pulse.
Performance of MPPC for 50µm pitch device, unless noted
Key performance (1)

• Basic parameters
  • Gain
  • Noise
  • Photon detection efficiency
  • Timing resolution
Gain of MPPC can be measured with well-separated p.e. peaks: 

\[ \text{Gain} = \frac{Q}{e} \]

Using linear relation, breakdown voltage \( (V_{bd}) \) also derived.
Measured gain

- MPPC has ~$10^6$ internal gain.

HPK spec is $7.5 \times 10^5$ ($\Delta V \sim 1.3 V$)
Temperature dependence

• Many parameters of MPPC are known to depend on ‘over-voltage’ $\Delta V \equiv V - V_{bd}$

• $V_{bd}$ linearly depends on temperature $dV_{bd}/dT \sim -50 \text{mV/K}$
Dark noise rate

- Measured with scaler
- 1 p.e. noise dominates

~ order lower than other ‘SiPM’ type devices

Bias voltage [V]

- 69.2
- 69.6
- 70

Temperature [°C]

- 15°C
- 20°C
- 25°C

Dark noise rate [kHz]

- 0.5 p.e. threshold
- 1.5 p.e.
Photon Detection Efficiency (PDE)

• Probability of detecting single photon entering the surface of device

• Three major components:
  • Geometrical efficiency
    (30/60/78% for 25/50/100µm pixles)
  • Quantum efficiency
  • Probability to trigger Geiger avalanche
    • Depends on over-voltage.
Photon Detection Efficiency

• Measured using PMT (bialkali, QE~15% by catalogue) as reference
• Compare detected number of p.e.
• Light source: Blue LED (Nichia NSPB500S, peak λ~470nm)
Photon Detection Efficiency

- PDE for MPPC is higher than PMT.

* p.e. for MPPC derived from pedestal fraction to avoid cross-talk and after-pulse effects.
PDE from catalogue

* Measured with current: includes effects from cross-talk and after-pulse.
Timing resolution

Measured w/ pulse laser
636 / 410nm

Sample MPPC
Bias -71.5V
Threshold 0.5pe
Only Single photon data

Time walk corrected.

T. Iijima @PD07
Key performance (2)

• Parameters under intensive study..
• Optical cross-talk
• After-pulse
• Radiation effects
Optical cross-talk

- Photons created during avalanche can enter neighboring pixels
- They can trigger additional avalanche → optical cross-talk
- Increase excess noise factor
After-pulse

- Carrier trapped in impurity state may be released after certain time and cause delayed avalanche in the same pixel, or after-pulse
- Also increase excess-noise factor
Measurement of cross-talk and after-pulse

Charge (ADC) distribution

Fraction of pedestal events

Poisson statistics

Estimate `true' 1 p.e. events

Comparison

Observed 1 p.e. events

Probability of cross-talk & after-pulse

*Only combined probability can be measured with this technique.
Cross-talk & after-pulse

Gate width: 800ns

Cross-talk & after pulse rate 400pixel

Cross-talk & after pulse rate 400pixel : $\Delta V$

Significant effect observed. Depends on over-voltage.

S. Gomi
(Kyoto)
Possibility of cross-talk suppression

Al optical separation

Trench etching

K. Yamamoto @ PD07
Study of after-pulse

- Special structure with only one pixel
- No cross-talk effect
- Pixel structure identical to usual ones
- Using delayed gate with self-trigger, measure time constant of after-pulse
Measured time constant

- ~50ns for 50µm pixel (~150ns for 100µm)

More study in near future.

S. Gomi
(Kyoto)
Radiation effects

- Several studies in Japan:
  - $\gamma$-ray irradiation with $^{60}$Co
  - Proton irradiation at RCNP 53.3MeV cyclotron
  - Neutron irradiation at reactor (ongoing, not reported here)
γ-ray irradiation

- Leakage current after every 40 Gy irradiation
- Annealing observed

Leakage current at $V_{op}$ increased ~1.7 times by these irradiations.

Annealing effect was observed from 120 Gy irradiation.

Leakage current changed so much just after 200 Gy and 240 Gy.

$\begin{array}{cccccc}
\text{Leakage current after each irradiation} \\
\text{0.23 \mu A} & 10^{-1} & 1 & 10 & 10^{1} \\
\end{array}$

$\begin{array}{cccccc}
\text{Time [hour]} & 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\end{array}$

$\begin{array}{cccccc}
\text{Leakage Current [\mu A]} & 0.39 & 0.39 & 0.39 & 0.39 & 0.39 & 0.39 & 0.39 \\
\end{array}$

$\begin{array}{cccccc}
\text{Gy} & 0 & 40 & 80 & 120 & 160 & 200 & 240 \\
\end{array}$

$\begin{array}{cccccc}
\text{[Gy]} & (\Delta V = 1.2, 25^\circ C) \\
\end{array}$

T. Matsubara
@PD07

M. Yokoyama @ SLAC AIS, 8/22/2007
No significant change was observed. Variation of the gain within the systematical effect by temperature.

Gain vs Bias voltage

Noise rate vs Bias voltage

Crosstalk vs Bias voltage

For crosstalk, no significant change was observed.
Proton irradiation

leakage current after 1 hour (μA) vs. accumulated dose (Gy)

- Sample #20 (130 Gy/h)
- Sample #21 (16 Gy/h)

T. Matsumura @PD07
Proton irradiation

Photon-counting capability is lost due to baseline shifts and noise pile-up after 21 Gy irradiation.

Sample #21 (16 Gy/h)
- 0 Gy: noise rate 270 kHz
- 2.8 Gy: 6.9 MHz
- 5.5 Gy: >10 MHz
- 8.0 Gy: >10 MHz

Sample #20 (130 Gy/h)
- 0 Gy: noise rate 270 kHz
- 21 Gy: >10 MHz
- 42 Gy: >10 MHz

gate width: 55 ns

Noise-rate measurements were limited due to scaler performance.

T. Matsumura @PD07
Are you interested?

- Many **advantages**:
  - High \((10^5-10^6)\) gain with low voltage (<100V)
  - High photon detection efficiency
  - Compact and robust
  - Insensitive to magnetic fields

- Although as many **possible drawbacks at this moment**:
  - Only small size (typically \(\sim\text{mm}^2\)) available
  - High dark count rate (100kHz-1MHz/mm\(^2\))
  - Optical cross-talk and after-pulse
For more information,

- Workshop for photodetectors, especially focusing on Geiger-mode APDs, was held in June at Kobe.
- Presentations are available on the web.

http://www-conf.kek.jp/PD07/

- ‘PD08’ will be held in fall 2008 in Matsumoto (central Japan).
Final remarks

- MPPC (and other pixelized Geiger-mode APD) has many attractive features.
- Still new device:
  - There is much room for improvement/optimization
  - Many intense R&D ongoing over the world
  - Direction of development depends on usage
  - Important parameters different for each application
Hope this talk helps to understand current situation and to design your experiment!

<table>
<thead>
<tr>
<th></th>
<th>Gain</th>
<th>Noise</th>
<th>Dynamic range</th>
<th>PDE</th>
<th>Cross-talk</th>
<th>Cost</th>
<th>......</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pixels</td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ΔV</td>
<td>+</td>
<td>+</td>
<td></td>
<td>+</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp</td>
<td></td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
<td>?</td>
<td></td>
</tr>
<tr>
<td>Special structure</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>–?</td>
<td>+?</td>
<td></td>
</tr>
<tr>
<td>Active area</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
<td>+</td>
<td>+?</td>
<td></td>
</tr>
</tbody>
</table>

* Not a complete table but biased by personal view
** There may also be correlation...
Thanks!
Backup
MPPC structure

- Used for CMS-ECAL APD
- Better quantum efficiency to shorter wavelength

Usual device:
- \( n^+ \) on \( p/p^- \)

‘Reverse structure’: \( p^+ \) on \( p^- \) epi

K. Yamamoto @ PD07
Photo Absorption coefficient of Silicon
Ionization rate (cm⁻¹) vs. electric field (× 10⁵ V/cm)

- Electron (α)
- Holes (β)

Ionization coefficient for avalanche multiplication.
Dynamic range

- Intrinsically limited by finite number of pixels
- Affected by cross-talk probability
- Also depends on time structure of input photons

![Graph showing dynamic range](image)
Dynamic range is enhanced with longer light pulse,
- Time structure of the light pulse gives large effects in non-linear region.
- No significant influence with changing bias voltage.
- Knowing time structure of scintillator light signal is crucial
  -> study is ongoing.
Recovery Time Measurement

- Inject blight laser pulse (width=52 ps) into the MPPC
- After delay of $\Delta t$, inject blight LED light pulse, and measure MPPC output for the LED pulse.
- Compare the MPPC output for the LED pulse with and without the first laser pulse.

Black … MPPC output for Laser pulse
Green … MPPC output for LED pulse
Red … Laser + LED
Blue … (Laser+LED) - Laser

Ratio of Blue / Green shows recovery fraction.
Recovery Time Result

The curve is fitted by a function

\[ f(\Delta t) = A(1 - e^{-(\Delta t-t_D)/\tau}) \]

\( t_D \): dead time  
\( \tau \): recovery time

- Recovery time of the 1600-pixel MPPC \( \sim 4 \text{ ns} \). 
- The shape does not depend on bias voltage.

\[ V_{\text{bias}} = \begin{align*} & 71.0 \text{ V} \\
& 71.5 \text{ V} \\
& 72.0 \text{ V} \end{align*} \]

<table>
<thead>
<tr>
<th>( V_{\text{bias}} ) (V)</th>
<th>( \tau ) (nsec)</th>
<th>( t_D ) (nsec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>71.0</td>
<td>4.1 ( \pm ) 0.1</td>
<td>1.9 ( \pm ) 0.1</td>
</tr>
<tr>
<td>71.5</td>
<td>4.0 ( \pm ) 0.1</td>
<td>1.7 ( \pm ) 0.1</td>
</tr>
<tr>
<td>72.0</td>
<td>4.2 ( \pm ) 0.1</td>
<td>1.3 ( \pm ) 0.1</td>
</tr>
</tbody>
</table>

at 25°C
• **Beam intensity** ... monitored with two plastic scintillates
Variation of the leakage current (higher flux irradiation)

Sample #20
2.3 × 10^5 protons/mm²/s (130 Gy/h)

- The leakage current lineally increases with irradiated doses.
- Annealing effects are seen. But the radiation damage is not completely recovered within a few hours.
Variation of the leakage current (lower flux irradiation)

Sample #21
3.0×10^4 protons/mm^2/s (16 Gy/h)

- Similar tendency was observed as the higher-flux irradiation except for increasing rates of the leakage current.

T.Matsumura @ PD07