Study of the Mechanisms of Pixelated Photon Detector (PPD)

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What is Pixelated Photon Detector (PPD)?

Pixelated Photon Detector (PPD) consists of multi-pixel APDs operated in a Geiger-mode. Each pixel has single photon countability.

Active R&D all over the world

SiPM, MPPC, MRS-APD, SPM, AMPD, SSPM, GM-APD, SPAD, ………

e.g. MPPC

1600 pix in 1mm²

From the 2008 Review of Particle Physics, by PDG

**Characteristics of PPD**

**Picture of PPD for our measurement**
(1600 pix MPPC: S10262-11-025 produced by Hamamatsu Photonics K.K.)

- **Diode** ($C_d$)
- **Quenching Resistor** ($R_q$)

Many pixels in parallel

**Other Characteristics**

- High photon detection efficiency
- Magnetic tolerance
- Ultra-thin and compact body
- Robustness
- Low cost
- Low power consumption

**Applications**

- T2K for neutrino physics
- ILC for high energy physics
- MAGIC/EUSO for astroparticle physics
- PET in medical field…

**PPD could be a successor to PMTs.**

Each pixel has a single photon sensitivity
**Motivation of our study**

Issues of PPDs: **lower gain, higher thermal noise rate and smaller active area.**

<table>
<thead>
<tr>
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<th>PMT (R6091)</th>
<th>PPD (1600 pix MPPC: S10262-11-025)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gain</strong></td>
<td>$5 \times 10^6$</td>
<td>$2.75 \times 10^5$</td>
</tr>
<tr>
<td><strong>Dark noise rate</strong></td>
<td>2kHz</td>
<td>300kHz</td>
</tr>
<tr>
<td><strong>Active area</strong></td>
<td>$\Phi 65\text{mm}$</td>
<td>$\square 1\text{mm} \times 30.8%$</td>
</tr>
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In this talk, we propose a new structure which could have **higher gain with lower noise.**
The mechanism of generating waveform and
Proposal of a structure for higher gain
Waveforms at low temp.

Waveforms of PPD (MPPC) at 200K and 77K cannot be explained by conventional model.

<table>
<thead>
<tr>
<th></th>
<th>300K</th>
<th>200K</th>
<th>77K</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_q$</td>
<td>0.21MΩ</td>
<td>0.40MΩ</td>
<td>1.68MΩ</td>
</tr>
<tr>
<td>$C_q$</td>
<td>22.1fF</td>
<td>22.0fF</td>
<td>22.1fF</td>
</tr>
</tbody>
</table>

For other characteristics at low temp., see PoS(PD07)007, PD07 Proceedings.

Conventional model of PPD

+ Waveform is characterized only by $\tau = R_q C_d$
+ Realistic avalanche process does not included
  - avalanche process suddenly starts
  - avalanche process is instantly terminated.

For the reproduction of the waveform at various temperature, the origin of the spike component and the realistic avalanche process are crucial.
Our proposed model for PPD

We have included stray capacitance $C_q$ into our model which C. Piemonte pointed out as the origin of the spike component. (See IEEE Trans. Nucl. Sci, Vol 5, pp 236-244, 2007)

We have included realistic ionization probability into our model which make it possible to simulate transient multiplication.
Reproduction of the waveforms

From our model, two equations are obtained and solved numerically.

\[
\begin{align*}
\frac{dq(t)}{dt} &= \sum_{i=e,h} e \rho_i(x) v \alpha_i(V_{d(t)}) \, dx^3 \\
\frac{dV_d(t)}{dt} &= \frac{1}{R_q(C_d + C_q)} (V_{op} - V_d(t) - R_q \frac{dq(t)}{dt})
\end{align*}
\]

\( R_q \) and \( C_d \) are already obtained as already referred. Remaining parameter, \( C_q \), is also evaluated from the spike component at 77K.

For details, see arXiv0808.2541v1
Submitted to Nucl. Instr. and Meth.
Determination of $C_q$ value

All parameters for the waveforms at 200K and 300K are already obtained. We evaluate the comparison between measured and expected waveforms.

From the waveform at 77K, $C_q$ is determined as 2fF.
Checking the validity of our model

From the waveform at 77K, $C_q$ is determined as 2fF.

The difference of waveforms is reduced to only the difference of $R_q$ among the temperatures.
Reproduction of the gain

It is known that the gain of PPD can be expressed by:

\[ \text{Gain} \propto C_d \Delta V, \]

where \( \Delta V = V_{\text{operation}} - V_{\text{breakdown}} \).

From our model, voltage dependence of the gain is also reproduced.

\[ \text{we propose a structure to increase the gain from } C_d \Delta V \text{ to } (C_d + C_b) \Delta V. \]
Proposal of a structure for higher gain

Our proposal is to add a buffer capacitor $C_b$, parallel to the diode of the pixel. Once the multiplication starts in $C_d$, whole stored charge $(C_d + C_b)\Delta V$ is released. There is no multipl. layer in $C_b$, thus the source of the thermal noise does not increase.

As a result, the gain increases to $(C_d + C_b)\Delta V$, while thermal noise remains the same.
The mechanism of generating thermal noise
and
Proposal of a structure for lower gain
PPD (MPPC) structure

The structure of p-on-n type PPD

Guard Ring

Multiplication Layer

Drift Layer

Depletion Layer

Substrate

photon

~ $3 \times 10^5$ [V/m]

Geiger-mode avalanche field

Hidetoshi Otono
Simulation of avalanche probability

Avalanche probability:
the probability that a particular carrier occurs a Geiger-mode avalanche multiplication

Results

Avalanche probability plays a crucial role in the voltage depend. of PDE and thermal noise rate.
Blue light is absorbed near the surface because its absorption length is ~0.5μm.

Photon detection efficiency (PDE) for blue light
\[ \text{PDE} = \text{Absorption efficiency} \times \text{Avalanche probability} \]

Thermal noise
\[ \text{Thermal noise} = \text{Thermal excitation carriers} \times \text{Avalanche probability} \]

It is suggested that thermal noise is occurred mainly by holes.
Proposal of a structure for lower noise

Thermal excitations is generated all over the depletion layer. From the measurement, the depletion layer below the multipl. layer seem to be the main source of random noises.

Note that depletion layer above multipl. layer does not be changed.

Our proposed structure makes the noise rate lower and Photon Detection Efficiency remains the same.
Summary and Proposal of a new structure
Summary and Proposal of a new structure

Pixelated Photon Detector consists of multi-pixel APDs operated in a Geiger-mode.

We have developed a model including realistic avalanche process and stray capacitance, from which we properly reproduce output waveform and gain of PPD.
(See arXiv0808.2541v1 submitted to Nucl. Instr. and Meth. A)

We have studied the origin of noises such as thermal noise, crosstalk and after-pulsing, from which we evaluate how the performance of the present device is limited.
(We will submit to Nucl. Instr. and Meth. A soon)

With these result

We propose a new structure which could have higher gain with lower noise:
• To add a buffer capacitance parallel to diode,
• To shrink the depletion layer.

We are now studying this structure with semiconductor device/process simulator.

Thank you for your attention.
Radiation hardness (T.Matsumura@IEEE2008)

- Radiation hardness is one of the issue to be made clear for a practical use of MPPC. KEK-DTP has been performed a series of irradiation experiment with different rad. sources.

- **Mechanism of radiation damage**
  - neutrons / protons: bulk damage (dominant)
  - γ-rays: electric property change due to charge trapping near the Si-Insulator interface

- **Our present work**
  - γ-ray irradiation for special samples with different structure to improve radiation hardness against γ-rays.
  - Result
    - sample A was more γ-rays-resistant MPPC than conventional products.
    - sample B: ~220 Gy (conventional)
    - sample A: >600 Gy
R&D all over the world (T. Nakaya @Pixel2008)

Old map: now more exist...