Study of Afterpulsing of MPPC with Waveform Analysis

ICEPP, U Tokyo

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for Photon Sensor Group in KEK Detector Technology Project
2. Recording waveforms with digital oscilloscope and doing offline waveform analysis
3. Extraction of afterpulsing events

→The information about Recovery is obtained.
The Afterpulsing

- When original pulsing has occurred, some of the avalanching electrons are trapped at lattice defects in the crystal of the pixel.

- They are re-emitted in several time, and cause succeeding pulses.

- This phenomenon is known as “Afterpulsing”, and is distinguished from ordinary thermal pulsing.

- Afterpulsings occur in the same pixel that the original pulsing occurred just before.

- Because recovery process and afterpulsing are unrelated to each other, afterpulsings can occur during recovering.

- We can probe recovery process by measuring afterpulsing.
Extraction of Afterpulsing Events

O : original pulsing
A : afterpulsing
C : crosstalk(s)
N : accidental noise
(AC) : afterpulse caused crosstalk(s)

Various Signals
- O
- O+N
- O+A
- O+(AC)
- O+A+A
- C
- C+A
- C+(AC)
- C+A+A
- etc...
Extraction of Afterpulsing Events

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Extraction of Afterpulsing Events

Various Signals

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<tr>
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O : original pulsing  A : afterpulsing  C : crosstalk(s)  N : accidental noise  (AC) : afterpulse caused crosstalk(s)
Extraction of Afterpulsing Events

Original pulsing

Various Signals
- O: original pulsing
- O+N: original pulsing with accidental noise
- O+A: original pulsing with afterpulsing
- O+(AC): original pulsing with afterpulse caused crosstalk(s)
- O+A+A: original pulsing with afterpulsing and accidental noise
- C: crosstalk(s)
- C+A: crosstalk(s) with afterpulsing
- C+(AC): crosstalk(s) with afterpulse caused crosstalk(s)
- etc...

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Extraction of Afterpulsing Events

Various Signals
- O
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- etc...

Original pulsing
O : original pulsing
A : afterpulsing
C : crosstalk(s)
(N) : accidental noise
(AC) : afterpulse caused crosstalk(s)
PulseHeight of Afterpulsing is recovering clearly
The Afterfraction

GND

Thr.
The Afterfraction

GND
Thr.
PulseHeight

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The Afterfraction

Original Charge

GND

Thr.

PulseHeight

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The Afterfraction

Original Charge

GND

Thr.

PulseHeight

Afterpulse Charge
The Afterfraction

Original Charge

Afterpulse Charge

GND

Thr.

PulseHeight

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The Afterfraction

Original Charge

Afterpulse Charge

= Afterfraction
The Afterfraction

GND
Thr.

Original Charge

PulseHeight

Afterpulse Charge

= Afterfraction

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The Afterfraction

Original Charge

GND

Thr.

PulseHeight

Afterpulse Charge

Interval Time

= Afterfraction

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The Afterfraction

Plot the interval time vs. afterfraction for each event

Original Charge

Afterpulse Charge

GND

Thr.

PulseHeight

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The Afterfraction

Plot the interval time vs. afterfraction for each event.

Afterfraction = Afterpulsing

Original Charge

GND

Thr.

PulseHeight

Afterpulse Charge

Interval Time

Afterfraction

0

1

Interval Time

Afterpulsing

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The Afterfraction

\[ \text{Afterfraction} = \text{Afterpulse Charge} / \text{Original Charge} \]

Plot the interval time vs. afterfraction for each event.

The scattering plot composes Recovery Curve of afterpulsing.

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The Afterpulse

= Afterfraction

Interval Time

Plot the interval time vs. afterfraction for each event

The scattering plot composes Recovery Curve of afterpulsing.

Accidental noise

Afterpulsing

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40x40 Pixels MPPC Recovery Curve

Measurement
- 50% recovery: ~ 3 [ns]
- 90% recovery: ~ 9 [ns]

Fitting
- 63% (=1-1/e): ~ 4 [ns]
  (Fitted to $1 - \exp\left[-t/\tau\right]$)

Measurement Conditions
- Bias Voltage: $V_0 + 3.3$ [V]
- Temperature: ~ 300 [K]
- Sampling Rate: 200 [ps/Sample]
- Noise Reduction: ERES*, bit=2.0
- Charge Estimation Gate: -5 ~ 60 [ns]
40x40 Pixels MPPC Recovery Curve

Measurement
- 50% recovery : ~ 3 [ns]
- 90% recovery : ~ 9 [ns]

Fitting
- 63% (=1-1/e) : ~ 4 [ns]
  (Fitted to $1 - \exp\left[-t/\tau\right]$)

Measurement Conditions
- Bias Voltage : $76.90 = V_0 + 3.3$ [V]
- Temperature : ~ 300 [K]
- Sampling Rate : 200 [ps/Sample]
- Noise Reduction : ERES*, bit=2.0
- Charge Estimation Gate : -5 ~ 60 [ns]
40x40 Pixels MPPC Recovery Curve

Measurement
- 50% recovery : \(\sim 3\) [ns]
- 90% recovery : \(\sim 9\) [ns]

Fitting
- 63% \((=1-1/e)\) : \(\sim 4\) [ns]
(Fitted to \(1 - \exp\left[-t/\tau\right]\))

Measurement Conditions
• Bias Voltage : \(76.9 = V_0 + 3.3\) [V]
• Temperature : \(\sim 300\) [K]
• Sampling Rate : 200 [ps/Sample]
• Noise Reduction : ERES*, bit=2.0
• Charge Estimation Gate : -5 \(\sim 60\) [ns]
Bias Voltage Variation

\[ V_0 + 4.2 \text{ [V]} \]

[Graph showing data with bias voltage of 77.84 [V].]

\[ V_0 + 3.3 \text{ [V]} \]

[Graph showing data with bias voltage of 76.90 [V].]

\[ V_0 + 2.8 \text{ [V]} \]

[Graph showing data with bias voltage of 75.40 [V].]
Bias Voltage Variation

- $V_0 + 4.2 \text{ [V]}$
- $V_0 + 3.3 \text{ [V]}$
- $V_0 + 2.8 \text{ [V]}$

Bias Voltage Variation
Bias Voltage Variation

50% recovery : ~ 3 [ns]
90% recovery : ~ 9 [ns]
63% (=1-1/e) : ~ 4 [ns]

Recovery Curve does not vary significantly by bias voltage.
**20x20 Pixels MPPC Recovery Curve**

**Measurement**
- 50% recovery : $\sim 6$ [ns]
- 90% recovery : $\sim 19$ [ns]

**Fitting**
- 63% ($=1-1/e$) : $\sim 9$ [ns]
  (Fitted to $1 - \exp[-t/\tau]$)

**Measurement Conditions**
- Bias Voltage : $70.36 = V_0 + 2.7$ [V]
- Temperature : $\sim 300$ [K]
- Sampling Rate : 200 [ps/Sample]
- Noise Reduction : ERES*, bit=2.0
- Charge Estimation Gate : $-5 \sim 60$ [ns]
Measurement

- 50% recovery : ~ 24 [ns]
- 90% recovery : ~ 77 [ns]

Fitting

- 63% (=1-1/e) : ~ 33 [ns]
  (Fitted to $1 - \exp\left[-t/\tau\right]$)

Measurement Conditions

- Bias Voltage : 69.62 = V₀ + 0.87 [V]
- Temperature : ~ 300 [K]
- Sampling Rate : 400 [ps/Sample]
- Noise Reduction : ERES*, bit=2.5
- Charge Estimation Gate : -15 ~ 150 [ns]
## Relationship between Recovery and Time Const.

<table>
<thead>
<tr>
<th>Afterpulsing 1-1/e Recovery</th>
<th>~ 4 [ns]</th>
<th>~ 9 [ns]</th>
<th>~ 33 [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Shape returning time (RC Time Const.)</td>
<td>~ 5 [ns]</td>
<td>~ 11 [ns]</td>
<td>~ 35 [ns]</td>
</tr>
</tbody>
</table>

Afterpulsing recovery time are consistent with pulse shape returning time.
Summary

- Dark noise @ 300 [K]
- Afterpulsing Extraction
- Offline Waveform analysis

Recovery Curve is obtained.

Voltage Dependence

<table>
<thead>
<tr>
<th>Size</th>
<th>Voltage</th>
<th>Recovery Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>40x40 px</td>
<td>76.40 [V]</td>
<td>3 [ns]</td>
</tr>
<tr>
<td>50%</td>
<td>76.90 [V]</td>
<td>3 [ns]</td>
</tr>
<tr>
<td></td>
<td>77.84 [V]</td>
<td>3 [ns]</td>
</tr>
<tr>
<td>63% (1-1/e)</td>
<td>4 [ns]</td>
<td>4 [ns]</td>
</tr>
<tr>
<td>90%</td>
<td>9 [ns]</td>
<td>9 [ns]</td>
</tr>
</tbody>
</table>

- Recovery Curve does not change significantly by bias voltage.

MPPC Type Variation

<table>
<thead>
<tr>
<th>Size</th>
<th>Voltage</th>
<th>Recovery Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>40x40 px</td>
<td>76.90 [V]</td>
<td>3 [ns]</td>
</tr>
<tr>
<td>20x20 px</td>
<td>70.36 [V]</td>
<td>6 [ns]</td>
</tr>
<tr>
<td>10x10 px</td>
<td>69.62 [V]</td>
<td>24 [ns]</td>
</tr>
<tr>
<td>50%</td>
<td>3 [ns]</td>
<td>6 [ns]</td>
</tr>
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</tr>
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<td>90%</td>
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<td>19 [ns]</td>
</tr>
</tbody>
</table>

- Afterpulsing recovery time are consistent with pulse shape returning time.
Prospects

- More sharp and precise recovery curve will be obtained by improving waveform analysis method.

- We are now planning to study recovery using two laser pulses shooting the same pixel of MPPC in a row, with short-time interval down to 1 [ns] or shorter.
Backup
The Recovery

- MPPC is a PIN-junction semiconductor device, and is operated at Geiger-mode.

- After avalanche occurrence, bias voltage goes down to the Breakdown Voltage $V_0$. There must be time for recovery to the Operating Voltage $V_{\text{op}}$.

- During recovering, bias voltage is less than $V_{\text{op}}$. The amplitude of pulses are smaller than that under $V_{\text{op}}$. 
The Oscilloscope

- LeCroy WavePro 7300A
- Digital Oscilloscope
- OS: Windows XP
- Bandwidth: 3 [GHz] @ 50 [Ω]
- Maximum Sampling Rate: 20 [ps/Sample]
- Vertical Resolution: 8bit
Noise Reduction

- We used LeCroy ERES (Enhanced RESolution) filtering.
- It is similar to smoothing with moving-average filter, but is more efficient concerning bandwidth and pass-band filtering.
- We used the mode 2.0.
- Sampling Rate: 200 [ps/Sample] for 200 [ns] (1k pts/file)

<table>
<thead>
<tr>
<th>Resolution increased by</th>
<th>-3 [dB] Bandwidth (x Nyquist)</th>
<th>Filter Length (Samples)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>1.0</td>
<td>0.241</td>
<td>5</td>
</tr>
<tr>
<td>1.5</td>
<td>0.121</td>
<td>10</td>
</tr>
<tr>
<td>2.0</td>
<td>0.058</td>
<td>24</td>
</tr>
<tr>
<td>2.5</td>
<td>0.029</td>
<td>51</td>
</tr>
<tr>
<td>3.0</td>
<td>0.016</td>
<td>117</td>
</tr>
</tbody>
</table>
Noise Reduction

signal source

ERES Filtered waveform
Waveform
Example

Afterpulsing caused Crosstalk : N+(AC)

Accidental Noise (inference) : O+N

Afterpulsing : O+A
The Proportionality of Pulseheight and Charge

- We used the proportionality of pulseheight and charge for estimating the charge of Original pulsing.

- ERES mode filter distorts the waveform, but it does not change the integral of the pulse.

- We measured the relationship between the (filtered) pulseheight and the charge of Normal pulsing.
Original Charge Estimation

Example: 40x40 px MPPC

End point of integral is chosen to satisfy the condition that original pulses are sufficiently filled up.
Charge Afterfraction vs. Pulseheight Afterfraction

Events which afterpulsing occurred later than 70 [ns] of 40x40 px MPPC (recovered stage)

Pulse afterfraction (PAF) vs. Charge afterfraction (CAF)

Bias Voltage: 76.90[V]

No Correlation

Original charge estimation is accurate.

Original Charge

PulseHeight

98.9 ± 0.4 %

99.4 ± 0.2 %

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<table>
<thead>
<tr>
<th>MIN</th>
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</tr>
</thead>
<tbody>
<tr>
<td>MAX</td>
<td>MAX</td>
</tr>
</tbody>
</table>
DATA
ERES Filtered
200 ps for 200 ns
HV: -76.85 V
Thr: -20 mV

1st Pulse Trigger
Thr: -20 mV

1st Pulse PeakFind

Number of Peaks

Otherwise

Exclude

2nd Pulse PeakFind

Number of Peaks

Otherwise

Exclude

Exist Any Pulses until 80 ns after Original Pulse

Calculate Charge

Calculate Afterfration

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO

YES

NO
Recovery Fitting

Bias Voltage: 76.90[V]

Fitting function: $1 - \exp[-t/\tau]$

$\tau = 4.10 \pm 0.02$

(statistical error only)