Study of Timing Properties of SiPMs at Fermilab

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Abstract. We continue our timing measurements of Silicon Photomultipliers (SiPM) at the picosecond level at Fermilab. We using SiPMs readout based on Ortec system \cite{1}, also as on fast waveform digitizer DRS4 \cite{2}. SiPM’s signal pulse shape was investigated. The single photoelectron time resolution (SPTR) was measured for the signals coming from the SiPM’s. Dependence of the SPTR on the SiPMs size was measured. Results of the last test beam with SiPMs are presented.

SiPM Signal Shape, (SSS).

It is well established that SiPM signal shape does not depends significantly on numbers of detected photons, \(N_{ph} \), when SiPM illuminated by short light pulse (\(N_{ph} \ll N_{c} \)). \(N_{c} \) is number of SiPM’s cells. SiPM signal consists of 3 main parts (Fig. 1): rise time, recovery time and fast spike on leading edge in presence of parasitic capacitance. Rise time is mostly relates with avalanche development in SiPM, recovery time manages by diode charge through quenching resistor and fast spike on the signal leading edge depends on diode’s parasitic capacitance magnitude.

A library of traces of all tested SiPMs: STM, MPPC, SensL, CPTA, KETEK, FBK-IRST, MRS was settled. The library is used for SiPM output signal modeling with different light sources.

Single Photoelectron Time Resolution, (SPTR).

If we know the SPTR we can estimate the SiPM time resolution for some number of photoelectrons \(N_{ph} \) by using the formula:

\[
\sigma = \frac{\text{SPTR}}{\sqrt{N_{ph}}}
\]

We have to note that the formula is only true when the light pulse shape does not change with the number of the photons increase, i.e. the number of the photoelectrons enhances due to light density (also as not to light pulse duration).

The time distribution (SPTR) of the SiPM signals originated by single photon relative to trigger signal was measured. It is easy to identify single photoelectron by SiPM. We have to clip the SiPMs signal when measuring the SPTR with Ortec 9327 constant fraction discriminator, Fig. 2. Fig. 3 shows the effect of clipping capacitance on SSS.

![Fig. 1. STM trace, 3.5x3.5 mm\textsuperscript{2}. 3,600 cells. N on P structure. PiLas light.](image1)

![Fig. 2. Schematic of the SiPM clipping circuit.](image2)
Influence of the SiPM structure on SPTR was observed. A picture of the electric field distribution for the shallow junction SiPM produced by STM is shown in Fig. 4. For N on P junction the n+ side of the silicon faces the light. One can see that if a photon absorbs close to the SiPM surface then the originated carriers will be holes. Likewise, the carriers will be electrons if the photon is absorbed deep into the silicon. The absorption length is about 100 nm for the 405 nm photon (blue light PiLas head) and 4 um for the 635 nm (red light PiLas head).

Thus, blue photons produce mostly holes, which travel to the high electric field and eventually develop an avalanche (N on P structure). The red photons produce mostly electrons traveling into the high field from the opposite direction. The mobility of holes in silicon’s electric field is about 3 times less than for electrons, but the holes path length is 40 times less. So the combined time spread of carriers originated by blue photons should be about one order of magnitude less than that originated by red photons.

This could explain why the SPTR is better for the blue light, Fig. 5.

The magnitude of the velocity of carriers inside of silicon is about 1-10 ns per 300 um, depending on the electric field applied, silicon impurity and temperature. According to a rough estimation, a spread on the order of a few microns of travel distance could provide 100 ps of the corresponding time spread. This simple picture does not take into consideration the time jitter due to an avalanche development, lateral avalanche size, but only considers the initial carrier’s time spread. Nevertheless, this naïve model describes reasonably the data obtained for the N on P STM. For the STM with P on N structure the p+ side faces the light. The electrons are the carriers for the 405 nm, and the holes are for the 635 nm in this case. We found almost no significant SPTR difference for the 3.5x3.5 mm² STMs for 405 nm and 635 nm illumination, ~10% at most. We also do not see big SPTR difference for the STM of 1x1 mm², and the same cell size. The SPTR is at the level of 50 – 65 ps for both size 3.5x3.5 mm² and 1x1 mm². Fig. 6. The SiPMs show the SPTR improvement with the bias voltage increase, due to avalanche probability increase.
Fig. 6, top: SPTR for STM, P on N, 3.5x3.5 mm$^2$, 3,600 pixels, 58 um pitch. Bottom: The SPTR for STM, P on N, 1x1 mm$^2$, 324 pixels, 58 um pitch.

Fig. 7, top: SPTR for MPPC-S10362-33-050C, 3x3 mm$^2$. Pixel size: 50x50um$^2$. Bottom: SPTR for MPPC-S10362-11-025P, MPPC-S10362-11-050P, MPPC-S10362-11-100P, all 1x1 mm$^2$.

Fig. 7 presents same results for MPPC, 3x3 mm$^2$, and 1x1 mm$^2$ for different cell size. The figure shows some SPTR improvement with smaller SiPM pixel size. About 10 times capacitance increases for 3.5x3.5 mm$^2$ size in comparison with 1x1mm$^2$, should lead to significant rise time increase and to worse SPTR as result. But it was not observed experimentally. Also we did not find significant shape difference (especially T,) observed when the clipping capacitance used. The STM single photoelectron clipped signals presented in Fig. 8.

The signal’s shape is almost the same for STM 1x1 mm$^2$, but noise is lower. Nevertheless, we can conclude that increased single photoelectron noise for 3.5x3.5 mm$^2$ does not affect the SPTRs significantly. Almost the same SPTR (for about one order larger SiPM size) approves very good cells uniformity.

SPTR values for the MPPC-S10362-33-050C measured earlier were considerably larger. We use the same setup for the SPTR measurements which reproduce our old results. We can attribute these earlier results to the experimental MPPC samples, which were tested.

Table of some SiPMs parameters is presented below.

<table>
<thead>
<tr>
<th>SiPMs</th>
<th>Area, mm$^2$</th>
<th>PDE, %, 430 nm</th>
<th>SPTR, ps</th>
<th>BV, V</th>
<th>OV, V</th>
<th>Gain</th>
<th>Pixels amount</th>
<th>Pixel, um$^2$</th>
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<tbody>
<tr>
<td>STM</td>
<td>3.5x3.5</td>
<td>31, max</td>
<td>60-65</td>
<td>28</td>
<td>4</td>
<td>~10$^6$</td>
<td>3,600</td>
<td>60x60</td>
</tr>
<tr>
<td></td>
<td>1x1</td>
<td></td>
<td>50-53</td>
<td></td>
<td></td>
<td></td>
<td>324</td>
<td>60x60</td>
</tr>
<tr>
<td>MPPC</td>
<td>3x3</td>
<td>Up to</td>
<td>107-130</td>
<td>70</td>
<td>2</td>
<td>~10$^6$</td>
<td>3,600</td>
<td>50x50</td>
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<tr>
<td></td>
<td>1x1</td>
<td>50, max$^*$</td>
<td>80-120</td>
<td></td>
<td></td>
<td></td>
<td>400</td>
<td>50x50</td>
</tr>
</tbody>
</table>

*include effects of optical crosstalk and after pulsing.
Test Beam Results.

The setup for the measurements was installed at Fermilab Test Beam Facility, Fig. 9. We used readout based on ORTEC units, Fig. 10.

The MPPC with quartz radiator of 30 mm long were irradiated by 120 GeV proton beam at normal incidence. The obtained time resolution for MPPCs is 14 ps. Soft pulse height cuts applied. About the same result was obtained when we used DRS4 (Domino Ring Sampler) readout, introduced by Stefan Ritt, PSI. This is important because DRS4 has 200 ps/sample. 14.3 ps time resolution was obtained with STMs (per STM) and DRS4 readout, Fig. 11. DRS4 principle is based on sampling and storing an incoming signal in an Switch Capacitor Array (SCA), waiting for (selective) readout and digitization. DRS4 is capable to digitize 4 input channels at sampling rates 5 Giga-samples per second (GSPS, 200ps/sample). Individual channel depth is 1024 bins. BW is up to 850 MHz. DRS4 noise floor ~1 mV/50. DRS4 can replace old classic TDC, ADC traditional readout. PH and TR can be measured by the same unit.

Fig. 9. Test beam setup.

Fig. 10. Schematic diagram of the readout. CFD – constant fraction discriminator, TAC – time amplitude converter, ADC – analog to digital converter, ~16,000 channels, 3.1 ps/ch. Electronic time resolution for the readout ~2 ps.

Conclusion

We continue Fermilab TOF systems development. Our efforts are devoted to silicon photomultipliers and new readout, based on fast wave forms digitizers (e.g. DRS4).

We found simple method to improve time resolution by clipping SiPM signal.

The best time resolution obtained with STM in beam conditions is at level of 14 ps, sigma, (new STMs, new readout, DRS4, FTBF).
References