STUDY OF TIMING PROPERTIES
OF SILICON PHOTOMULTIPLIERS

Marcel Demarteau, Sergey Los, Erik Ramberg, Anatoly Ronzhin – Fermilab.

9/12/2008

1. Introduction

Time-of-flight (TOF) measurements for subatomic particles is a very useful technique to distinguish their species. Typical resolutions for TOF have been on the order of 100 picoseconds (psec). Partly this is due to the use of scintillators for light generation, which have extended generation times. Partly this is due to the inherent limitations of large size phototubes, whose intrinsic transit time spread (TTS) is large.

The multi-pixel avalanche photodiode, also know as a Silicon Photo Multiplier, or ‘SiPM’, could be an option for upgrading capabilities of TOF systems. The TTS of the SiPM is about 100 psec for a single photoelectron. The blue photon detection efficiency of the devices could be about 65%. So the level of a few tens of picoseconds for the TOF based on the SiPM’s with Cherenkov radiators looks achievable. We discuss here measurements of SiPM timing characteristics performed at the Fermi National Accelerator Laboratory (Fermilab).

2. Setups to study SiPM Timing.

Two setups at the Silicon Detector Facility (SiDet) at Fermilab were created for studying SiPM timing characteristics (Fig.1). The first one contains a dark box where SiPM’s under study are located. The parts of the setup are a picosecond-level pulse generator (Picosecond Pulse Lab, model 2000) used as a fast blue light emitting diode (LED) driver, and two SiPM’s hooked up to VT120C Ortec fast preamps and Ortec 934 Constant Fraction Discriminators (CFD). The LED light level was changed by a rotating wheel with light attenuation filters and monitored by PIN diodes. The LED attenuated light was delivered to the SiPM’s by optical fiber. The SiPM’s housing was mounted on a Peltier element which was used to change and stabilize the SiPM’s temperature. The Peltier allowed changing the temperature in the range of 0 C to +25C with 0.5 C of accuracy. The trigger out of the picosecond pulse generator was used as the timing start signal and the CFD signal as the stop. The time difference between the start and the stop signals was measured by an Ortec 567 Time to Amplitude Converter (TAC), whose analog output was fed into an Ortec AD114 14 bit Analog to Digital Converter (ADC), located in a CAMAC crate with PC readout. This system had 50 ns of dynamic range, with a single channel resolution of 3.1 psec.

The second setup also consisted of a dark box where SiPM's were placed. The SiPm output was connected with to an Ortec 9327 Ortec module (preamplifier and CFD combined in single unit). An Ortec VT120 attenuator was used between the SiPM out and 9327 input, when needed. The SiPM's were illuminated by a PiLas laser (635 nm head with light pulse duration of 40 ps). The PiLas allows changing of the light intensity in the dynamic range 0-100%. One can monitor the laser light by a PIN diode and a small size photomultiplier. A Peltier element was also used to stabilize the SiPm's temperature, but was eventually replaced by a "Ranque-Hilsch vortex tube" to increase the temperature dynamic range and improve temperature's stability. The range of temperature is +25C to -20C inside of the dark box. Four thermocouples were installed in different places inside and outside the box to achieve better temperature control. The temperature could be changed, stabilized and monitored with about 0.1C accuracy by hardware and software managed by a PC using Lab View software. The Pilas trigger signal is used as the timing start and the 9327 NIM out signal is used as the timing stop. The timing measurement is the same as the first setup. A Keithley supply was used for the SiPM's as a bias supply. The unit allows keeping supplied voltages at 10 mV accuracy.

3. Initial Tests of the Setups

Schematics of the initial test are shown in fig. 2 a,b,c. The start and stop signals were delivered to the TAC567 and AD114 from the same generator (fig. 2a). The so-called "electrical" time resolution was measured in this case and turned out to be 2 psec. Two peaks were obtained by introducing a 1000 psec delay into the stop signal (Fig. 3). The "warming up" time of the TAC567 plus AD114 is about 20 minutes. After half an hour the peak position is stable with +/- 1.5 psec during the next few hours at room temperature.

The next test was performed with a Hamamatsu MPPC with 1x1 mm^2 of sensitive area. This SiPM was illuminated by an intense LED. The driver pulse was used as a start signal and the SiPM as a stop signal (fig. 2b). The amount of LED light was enough to observe about ten psec time resolution. The mean timing peak position with respect to temperature and bias voltage was taken. A 11.5 psec time shift per 1 degree F of temperature was obtained in the temperature range 59-79 F for 1 Volt overvoltage on the bias for the SiPM. A 6.2 psec time shift per 10 mV of the bias change was revealed for the same 1 Volt of the overvoltage. These preliminary tests show conditions needed to keep a 10 psec level of time resolution. We attempted to keep these conditions in future tests.

One more test was performed with a piece of plexiglass, 5 cm of thickness, installed between the LED and the SiPM. The geometry of the test was chosen in such a way that the SiPM output signal was not changed when inserting and removing the plexiglass. The result is shown in fig. 4. The mean value of the timing peak position shifted positively by 77 psec with the plexiglass and returned back to the initial position when removing the plexiglass. This time shift is in very close agreement with the time delay for light passing through 5 cm of plexiglass (the index of refraction is 1.5) instead of 5 cm of air.

4. The **SiPM Timing Study**

We tested three Hamamatsu samples of 1x1 mm^2 of sensitive area: one with 100x100 μm^2 of pixel size (100 pixels on the device in total), one with 50x50 μm^2 pixel size (400 pixels) and one with 25x25 μm^2 (1600 pixels). The IRST devices were 2.8 mm of diameter with 50x50 μm^2 pixel sizes (2500 pixels) and 1x1 mm^2 with 40x40 μm^2 pixel sizes (625 pixels total). The CPTA devices were 2.1x2.1 mm^2 of sensitive area with pixel size 50x50 μm^2. A single photoelectron's timing (SPT) spread distributions were taken according to schematics (fig. 2c). The 9327 unit accepts pulse widths up to 5 ns. A simple clipping circuit was used to shorten the SiPM's pulses (fig. 5). The efficiency of the single photons registration was less than 10% with the chosen PiLas light intensity. The deposit of events with doubled single photoelectron's amplitude in the timing distribution could be neglected. The SPT at a level of 180 psec was obtained for most of the SiPM's when illuminated by a 40 psec light pulse with 635 nm wavelength. One Volt of overvoltage was applied to the SiPM's. A SPT of about 120 psec was obtained with higher overvoltage. Preliminary test of IRST SiPm show better single photoelectron time resolution (about 20%) when illuminating with blue laser light, 408 nm, with 1 Volt of the overvoltage. The time spread due to the Pilas light pulse parameters could be neglected in the measurements. An inverse square root dependence of the SiPM's time resolution was observed when we increased the number of photoelectron's detected. The number of photoelectrons was estimated on the base of the single photoelectron's signal which is perfectly defined for the SiPM's (fig. 6). Some tails or bumps were observed for some of the single photoelectron's time distribution (fig. 7). This effect could be referenced to optical crosstalk into some SiPM's as will be shown later. Most of the data were taken at room temperature under temperature control (73 +/-0.5 F).

5. Discussion

The dependence of light absorption length on wavelength in silicon is shown in fig. 8. The electric field dependence on distance from the SiPm surface is also shown on the same picture. The picture is taken from an article of H-G Moser, MPI [1]. A more precise picture of the electric field distribution for shallow junction SiPm produced by IRST, Italy [Claudio Piemonte report at Fermilab] presented in fig.9. One can see that if a photon absorbs close to the SiPM surface then the originated carriers will be holes for the IRST SiPm. Likewise, the carriers will be electrons if the photon is absorbed deep in the silicon. The absorption length is about 100 nm for 408 nm photon (blue light PiLas head) and 4 μm for 635 nm (red light PiLas head). So the blue photons produce mostly holes which travel to the high electric field and develop here an avalanche eventually. 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 hole's traveling distance is 40 times less. So the combined time spread of carriers originated by blue photons should be about one order of magnitude less than originated by red photons. This simple picture does not take into consideration time jitter due to avalanche development, lateral avalanche size, etc, but only considers the initial carrier's time spread. Nevertheless, this naïve model coincides to some extent with the obtained experimental data.

A tail was observed in the single photoelectron's time spectra for some of the SiPM's (fig 7). These spectra were taken with 0.5 photoelectron threshold of the 9327 unit. The significant enhancement of the events in the tail was observed with 1.5 photoelectron threshold (fig. 7). This meant that the tail is mostly composed by signals with doubled single photoelectron amplitude. Let's consider a simple model to explain this effect. It's already a well established fact that about one photon with more than 1eV energy is produced for every 100,000 electrons in a SiPM's avalanche [2]. The SiPM gain is about 10^6 usually, so each avalanche produces about 10 photons in average. Some of the photons, say instantly in the time scale of 100 psec, produce another charged carrier in neighboring pixels, which need time to get into the high field silicon area to create another avalanche. The signal of this avalanche is delayed with respect to the primary avalanche and overlaps with that initial one. The delay time could be of the order of hundreds to thousands of picoseconds depending on the distance between the originating avalanche and the high field area. The triggering time of the 9327 on such a superposition of the two single photoelectron signals should be a delayed output. This coincides with the obtained data as well as with the direct observation by an oscilloscope. The tail events mostly correspond to signals with doubled single photoelectron and delayed amplitude. The amount of the tail events increased with overvoltage. The observed tail in the single photoelectron time spectra is likely due to the optical crosstalk in the SiPM's. This phenomenon is well known. Some ways to suppress the crosstalk are proposed by producers [3]. We plan to order SiPM's with suppressed crosstalk and take its single photoelectron time spectra.

6. Summary of Results.

A new setup for timing measurements at the picosecond level has been arranged at Fermilab. The core timing resolution of the amplifiers, discriminators and TAC/ADC combination is approximately 2 picoseconds. We have made a study of single photoelectron time resolution measured for signals coming from silicon photomultipliers (SiPM) made by different manufacturers. The obtained single photoelectron time resolution (SPTR) is of the order of the 180 ps with the SiPM illuminated by the red (635 nm) PiLas laser light. For the IRST SiPm the SPTR is about 20% better when illuminating by the blue laser light (408 nm). The most of the data are taken with the 1 Volt of the overvoltage. The SPTR is better for higher overvoltage. The SiPM's time resolution is inversely proportional to the square root of the number of photoelectrons. A simple model is proposed to explain the difference in the single photoelectron time resolution when illuminating the SiPm by blue and red light. The explanation of the origin of the tail in the SiPM's single photoelectron time spectra is presented. The SiPM's temperature and bias voltage stability level to keep few picoseconds time resolution is discussed. A time of flight (TOF) system with a few tens of picosecond time resolution, based on SiPM's with quartz Cherenkov radiators, looks achievable.

Acknowledgements.

We appreciate Mike Albrow, Adam Para and Hogan Nguyen for their technical support and useful discussions.

References

1. Hans-Gunhter Moser. Silicon Photomultipliers, A New Device for Low Light Level Photon Detection. http://www.hll.mpg.de/Hauptnavigation/publications/2006/aip_867-98.pdf
2. Lacaita A, Cova S, Spinelli, and Zappa F. Photon-assisted avalanche spreading in reach-through photodiodes. Appl. Phys. Lett. 62 (6), 8 February 1993.
3. Claudio Piemonte. Development of Silicon Photomultipliers at IRST. FNAL report, October 25th 2006.