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Single photon time resolution of state of the art SiPMs

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Abstract: Comparison of the timing performance of different silicon photomultipliers (SiPMs) can be useful for applications that employ these devices. In our study, we characterize some of the currently available SiPMs to compare the single photon time resolution (SPTR) values measured using a 420 nm laser with a pulse width of 42 ps FWHM. SPTR values in the range of 175–330 ps FWHM were measured for most 3 × 3 mm² and 4 × 4 mm² devices and varied with the producer and the type of the SiPM. Factors influencing the SPTR including the area, cell to cell non-uniformity and the SPAD (single photon avalanche diode) jitter were investigated by the use of laser light focused at the level of a SPAD within a SiPM. The standard deviation of the SPTR values measured among different cells within a Hamamatsu Through Silicon Via SiPM was found to be less than 5 ps. When measured with focused laser the values of SPTR, the signal delay and the relative PDE were found to vary among different points within a SPAD of a SiPM. We found that such variation causes the values of SPTR measured with focused illumination to be better than when measured with diffuse illumination which probes the entire SiPM active surface. SPTR values close to 20 ps FWHM have been measured for standalone single SPADs produced by FBK after correcting for the laser jitter and the acquisition jitter. The performed tests helped us to understand the limits of the SPAD jitter. We infer that the dominant factor contributing to the degradation of the SPTR from the level of a SPAD to a SiPM is mostly driven by detector noise, if the influence of the signal delay time spread is reduced to a minimum.

Keywords: Gamma camera, SPECT, PET PET/CT, coronary CT angiography (CTA); Gamma detectors; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs etc); Timing detectors

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1 Introduction

The precision of a SiPM in determining the time of arrival of a single photon is referred to as the SPTR. SiPM single photon time resolution (SPTR) influences significantly the performance of detectors employed in various applications such as medical imaging [1], high energy physics experiments [2], homeland security [3], astroparticle physics [4], bio photonics [5] etc. Concerning PET application where two gamma photons are emitted from positron annihilation, an important parameter is the coincidence time resolution (CTR) measured with two detectors each comprising a SiPM coupled to a scintillating crystal. SPTR of a SiPM is one of the factors that affects the CTR [6]. The SPTR plays a major role in time of flight detectors employed in applications with low photon count such as Cherenkov detectors for particle identification. The SiPMs can be coupled to Quartz crystals, PbF$_2$, lead glass etc [7] in such applications.

Single photon avalanche diodes (SPADs) with excellent timing resolution values of 28 ps FWHM measured at room temperature were presented as early as 1989 by Cova et al., [8]. Several developments in SiPM technology over the last two decades have led to the production of devices with a higher photon detection efficiency, lower dark count rate and a superior timing performance. As an example for the application of SiPMs in time-of-flight positron emission tomography, CTR values of 85 ps FWHM have been measured with 3 mm long LSO:Ce codoped 0.4% Ca crystals coupled to FBK NUV $3 \times 3$ mm$^2$ SiPMs [9].
Since various producers have currently made available a number of SiPMs, understanding the timing performance among other factors such as the photon detection efficiency (PDE), dark count rate (DCR), etc., is necessary for the groups interested in applying the SiPMs or even in upgrading the experiments that currently employ photomultiplier tubes. This study reports the measured SPTR values of various devices available currently or in the near future for the market. Generally we denote the SPTR when measured with diffuse light incident on the entire SiPM surface. These results are presented in section 3. In the same section we compare the SPTR of some devices with a similar technology and different area to observe the effect of device size.

In order to better understand the factors influencing the time resolution, we also measured the SPTR with focused laser light. The focused SPTR measurements are described in section 4.1. Scanning for the SPTR by focusing at different points within a single SPAD, and by focusing multiple photons within the SPAD other contributions to the SPTR are investigated in sections 4.2. Through stand-alone single SPADs produced by FBK, we test the limits of SPTR measurement which will be presented in section 5.

2 Materials and methods

2.1 Devices and characteristics

To determine the operating range of voltages and the breakdown voltage for each of the devices, we performed a scan of the device current as a function of the reverse bias voltage under dark conditions. The breakdown voltage is obtained from the measured IV curve; a brief description of this procedure can be found in [10]. Table 1 describes different samples that were characterized, along with their cell size and device area specifications.

Description of the devices    Hamamatsu Through Silicon Via (TSV) is a technology where a through-via in the center of the SiPM is used to route the signal to the collection pins [11].

Table 1. List of SiPM samples from various producers and the breakdown voltages obtained from the measured IV characteristics.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>Device area (mm²)</th>
<th>Cell size (µm)</th>
<th>V_{breakdown} (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM</td>
<td>4.3 × 3.6</td>
<td>60</td>
<td>27.8 ± 0.1</td>
</tr>
<tr>
<td>FBK - Near Ultra Violet High Density</td>
<td>4 × 4</td>
<td>25</td>
<td>25.8 ± 0.1</td>
</tr>
<tr>
<td>FBK - Near Ultra Violet</td>
<td>3 × 3</td>
<td>40</td>
<td>26.2 ± 0.1</td>
</tr>
<tr>
<td>FBK - Near Ultra Violet</td>
<td>1 × 1</td>
<td>40</td>
<td>26.2 ± 0.1</td>
</tr>
<tr>
<td>FBK - Near Ultra Violet SPAD</td>
<td>0.04 × 0.04</td>
<td>40</td>
<td>26.2 ± 0.1</td>
</tr>
<tr>
<td>Hamamatsu Through Silicon Via</td>
<td>3 × 3</td>
<td>50</td>
<td>64.4 ± 0.1</td>
</tr>
<tr>
<td>Hamamatsu Through Silicon Via</td>
<td>2 × 2</td>
<td>50</td>
<td>64.9 ± 0.1</td>
</tr>
<tr>
<td>Hamamatsu Low Cross Talk 2</td>
<td>3 × 3</td>
<td>50</td>
<td>47.5 ± 0.1</td>
</tr>
<tr>
<td>SensL JD0</td>
<td>3 × 3</td>
<td>35</td>
<td>24.5 ± 0.1</td>
</tr>
<tr>
<td>SensL JD4</td>
<td>3 × 3</td>
<td>20</td>
<td>24.7 ± 0.1</td>
</tr>
<tr>
<td>Ketek Optimized</td>
<td>3 × 3</td>
<td>50</td>
<td>24.8 ± 0.1</td>
</tr>
</tbody>
</table>
An improvement in timing is expected due to a reduced path for the signal flow from the extreme positions to the SiPM output. The Hamamatsu Low Crosstalk (LCT) is a technology where trenches between neighboring SPADs in SiPM reduce the optical crosstalk. FBK Near Ultra Violet (NUV) devices have been developed with a process optimized for maximizing the PDE in the near ultra violet region as indicated by the name. FBK NUV-High Density (NUV-HD) devices are similar to NUV devices in terms of the quantum efficiency. The difference is that the SPADs in NUV-HD are smaller and more densely packed (25 $\mu$m for NUV-HD vs 40 $\mu$m for NUV). This enhances the dynamic range of these devices which have a higher fill factor and a lower correlated noise [12]. Due to a smaller cell size, the device operates at a lower gain and thus has a lower correlated detector noise. This enables the device to operate at very high overvoltages while still maintaining a good signal to noise ratio. The high overvoltages serve to increase the PDE of the device. We measured the performance of the latest version of Ketek namely ‘Ketek Optimized,’ which has optimized contact points from which the connections to the signal collection pins were made. This was made in order to achieve a better signal delay time spread. Two types of devices produced by SensL have been measured — JD0 and JD4. SensL-JD4 was optimized by the producers for a reduced signal delay time spread. SensL devices were operated in the regular configuration and not in the fast output as described in [13].

2.2 Experimental setup

The left part of figure 1 is a schematic representation of the experimental setup for the SPTR measurements. A 420 nm pico-second pulsed laser (PiLas) with a pulse width of 42 ps FWHM (measured using a streak camera at an optimal laser intensity of 50%) was used as a light source. The laser was set to operate at a repetition rate of 100 kHz and at a tuned intensity level of 50% as per the optimal operating conditions specified in the user manual. Light passes through a diaphragm that acts as a pinhole to reduce the size of the beam spot. A set of neutral density filters serve as optical attenuators that reduce the light intensity to the level of a single photon. This was later verified by checking the single photon spectrum of the SiPM. Diffused light is incident on the SiPM surface and the photons arrive at the surface of any of the SPADs within a SiPM with equal probability. This was achieved by an optical diffuser which expands the size of the beam to a larger area. The expanded beam with a diameter of $\sim$ 2 cm is approximated to have a uniform flux of photons in the chosen region illuminating the SiPM.

The central part of figure 1 is a schematic representation of the electronics and the signal flow for timing measurements with SiPMs. The SiPM is biased with a DC power supply and the output is fed into two channels — timing and voltage amplification. The NINO preamplifier discriminator [17] was used to determine the time stamp of the leading edge of the signal when it first crosses a set amplitude threshold. The time over threshold signal which contains the charge information is obtained in addition although we do not use it in this work. High pass filtering is implemented before the NINO input to reduce the long decay tails that otherwise lead to a baseline fluctuation. The voltage amplification channel comprises an instrumentation amplifier for acquiring the single photoelectron (p.e) spectrum. Due to a high input impedance of the amplification stage, the signal being fed into the timing channel remains unaffected. The electronics board described in [18] includes the described channels for timing and instrumentation amplifier and the output signals were acquired by a Lecroy oscilloscope (Waverunner 104Xi 1 GHZ, 10 GS/s) which is
2.3 Acquisition jitter

The input channel of the Lecroy oscilloscope, used to acquire the data, has a certain electronic noise. The amplitude has a Gaussian distribution with a measured sigma value of 1.25 mV. NINO rising edge has a finite slope causing the noise on the oscilloscope input channel to manifest as time jitter. This can be obtained by dividing the sigma of the noise amplitude by the slope of the NINO rising edge according to equation (2.1),

$$\sigma_{\text{NINO}} = \frac{\sigma_{\text{noise}}}{\frac{dV}{dt}},$$  

(2.1)

where $\frac{dV}{dt}$ is the slope of the NINO rising edge that is measured using the Oscilloscope and $\sigma_{\text{noise}}$ is the RMS noise floor of the oscilloscope plus NINO. This gives the acquisition jitter which has a value of $\sigma_{\text{NINO}} = 6$ ps.

The electronic trigger out of the laser is a square pulse with an amplitude of 1.4 V. The reference signal to measure the delay on the NINO signal output is the laser electronic trigger out as seen in figure 1. In order to estimate the jitter in the laser electronics trigger out, we split the laser signal into two channels and measured the jitter in the time difference. This value was measured to be $\sigma_{\text{trigger}} = 7$ ps (single trigger channel jitter in this case). The cumulative noise contribution is obtained by adding the two contributions coming from NINO and the laser trigger in quadrature ($\sigma_{\text{system}}^2 = \sigma_{\text{NINO}}^2 + \sigma_{\text{trigger}}^2$). This gives an estimated value of $\sigma_{\text{system}} = 9 \pm 1$ ps for the acquisition jitter.
2.4 Analysis

The time difference between the NINO rising edge and the laser electronic trigger out is referred to as the delay. Only the delays resulting from single photoelectron events are analyzed as seen in figure 1 (top right). We select for the events contained within the single p.e peak and plot the histogram of the delay signal. The full width at half maximum of this delay histogram yields the SPTR.

A Gaussian fit to the histogram as seen in figure 2 (left) does not account for the tail towards the right end of the spectrum. Such a tail, also observed by Puill et al., [7] and Acerbi et al., [16], can be a result of delayed signals generated by photons that get converted deeper in the junction. As photon absorption takes place with an exponential probability, the number of such delayed conversions will also go down exponentially. In view of this logic, we fitted the histogram with a function obtained by the convolution of the Gaussian and the exponential probability distributions as seen in equation (2.2). Such a function, called an exponentially modified Gaussian function, is described through equation (2.3) and was employed in the field of chromatography to analyze the chromatographic peaks [19]. The resulting fit accounts for the delay tail as seen in figure 2 (right).

\[
f(x; \mu, \sigma, \lambda) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \ast \lambda e^{-\lambda x}
\]

(2.2)

\[
f(x; \mu, \sigma, \lambda) = \frac{\lambda}{2} e^{\frac{1}{4}(2\mu+\lambda\sigma^2-2x)} \left[ 1 - \text{erf} \left( \frac{\mu + \lambda\sigma^2 - x}{\sqrt{2}\sigma} \right) \right],
\]

(2.3)

where \(\mu\) is the mean of the Gaussian distribution, \(\sigma\) is the standard deviation, \(\lambda\) is the exponential parameter (related to the contribution of the delay tail), and \text{erf}\() is the error function, which is described by

\[
\text{erf}(x) = \frac{2}{\sqrt{\pi}} \int_{0}^{x} e^{-t^2} dt
\]

(2.4)

**Figure 2.** Histogram of the time delay between the laser trigger and the NINO leading edge time stamp (detected signal time stamp). Left: histogram has been fitted with a Gaussian function. Right: histogram has been fitted with a Gaussian convolved with an exponential function.
As a comparison between the two fits from figure 2 a Gaussian fit yields a sigma of 79 ps while the fit function with Gaussian convolved with an exponential yields a sigma of 54 ps (corresponding value of $\lambda$ is 22 ns$^{-1}$). The FWHM of the fitted function yields a value of 175 ps while the Gaussian function, in comparison, yields a value of 186 ps. Contributions to the delay tail could come from additional factors such as the laser pulse profile and the SPAD delay non-uniformity (see section 4.2). Furthermore the stated function is achieved by a convolution having limits of positive and negative infinity, which is physically only an approximation in our case. For these reasons, we do not explore the details of the delay tail any further and use the function only to achieve a good fit.

All the reported values of SPTR are the full width at half maximum (FWHM) values of the Gaussian convolved with exponential fit function. The FWHM is estimated directly from the fitted analytical function and not from the fit parameter ($\sigma$ bears no direct relationship with the FWHM unlike a Gaussian function). Furthermore the reported values include the contributions due to the system electronic noise and the laser jitter.

2.5 Experimental setup for focused laser measurements

We investigated some of the contributing factors to the measured SPTR by focusing laser to the level of a single SPAD within a SiPM. The results of these studies will be presented in section 4.1. In this section we describe the experimental setup for focusing laser light and the techniques employed to verify the focusing at a single photon level.

The light beam output of the laser has a spot size of $1.2 \text{ mm} \times 2.7 \text{ mm}$. This spot size is a result of the optics that are a part of the construction of the laser head, where an initial beam of $1 \mu\text{m} \times 3 \mu\text{m}$ (from the laser head diode) is collimated by an aspherical lens with a focal length of 4.5 mm. With the intent of focusing the laser beam to a spot size of $< 10 \mu\text{m}$, we employed a converging lens with a focal length of 10 mm. The position of the optical system is kept fixed for the entire measurement while only the detector is moved along the X, Y and Z axes using linear motorized stages that precisely control the SiPM position.

![Figure 3](image_url)

**Figure 3.** Experimental schematic for the measurement of focused SPTR.

Making use of the three degrees of freedom in the positioning of the SiPM, optimal position is approximately chosen at first by visually inspecting the incident beam on the SiPM surface. When the beam is focused using a converging lens, positions closer or farther from the optimal point to the light source will result in de-focusing. This effect has been used to determine the precise position of
**Figure 4.** Plots that enable us to determine how precisely the laser light is focused. Left: variation of the single photo electron spectrum depending on the position of the focused beam spot along the XY plane. Right: relative PDE maps along XY axes that show the active regions and the inactive regions at a SPAD level of a SiPM. The figure in the bottom right represents a line scan with focused laser along two SPADs within a SiPM passing along the dead space. The deadspace can be identified through the drop in the relative PDE.

By counting the number of events contained within the 0 p.e peak relative to the total number of events, we arrive at the probability of detecting zero photons. Since the photon arrival rate follows Poisson statistics, we can use the probability of the 0 p.e event to determine the mean $\lambda$ of the Poisson distribution as shown in equation (2.5).

$$\lambda = -\log_e \left[ f(0, \lambda) \right],$$

where Lambda is the Poisson mean and $f(0, \lambda)$ is the probability of a 0 p.e event for the given mean obtained from a general Poisson distribution as shown in equation (2.6).

$$f(k, \lambda) = \frac{\lambda^k}{k!} e^{-\lambda},$$

where $k$, the photon number, is a variable representing the number of detected events.
The relative PDE is then obtained as shown in equation (2.7) by dividing
\[
\text{relative PDE} = \frac{\lambda}{\lambda_{\text{max}}},
\]
(2.7)

The plot on the right side of figure 4 represents the relative PDE in the neighborhood of a SPAD within a SiPM. In this figure the regions of low relative PDE correspond to the dead space between adjacent SPADs. The single p.e spectrum for the laser focused in the inactive region is seen to have a negligible count on the 1 p.e peak as seen in figure 4 (left-top). When the SiPM is aligned such that the focused laser spot is incident in the middle of the SPAD, a high number of counts is registered on the 1 p.e peak as seen in figure 4 (left-bottom). By scanning along various points at a SPAD level and analyzing the map of the relative PDE, we can identify the active and inactive regions of the SPAD. The contrast in the relative PDE values between the two regions indicates the level of focusing. This is illustrated further in figure 4 (bottom right) showing a finer line scan along two adjacent SPADs within a SiPM and the relative PDE values are plotted to indicate the deadspace. As the inactive region width is of the order of \(<10 \mu m\) which we can distinguish clearly (figure 4 right), we estimated the size of the focused spot to be of the order of \(\sim 5 \mu m\). This measurement helps us locate and focus the light on the center of a SPAD within a SiPM.

3 SPTR results for different samples

SPTR measurements with diffuse light characterize the performance of the whole device. The SPTR-diffuse is significant in its effect on the coincidence timing resolution where SiPMs are coupled with crystals since they uniformly illuminate the device. This value is generally reported in the literature [14, 15] and [16].

3.1 Results

Figure 5 shows the values of SPTR for various devices that we have characterized. It is important to note that the values of SPTR as a function of bias voltage are plotted for a constant discriminating threshold. This value of threshold voltage for each device is selected by optimizing it for the bias-voltage-setting that gives the best timing performance for that device. Such a chosen discrimination threshold value corresponds to about half the p.e level at that setting. Many studies, however, report the values of SPTR where the threshold voltage is optimized for each bias voltage which leads to slightly different values. Such analysis is possible when the signal waveforms are directly acquired and one has the flexibility to verify the timing at various threshold voltage levels. In a realistic acquisition however the threshold is usually set to be a constant and one cannot afford to acquire the waveform data for analysis due to the file size.

Figure 5 reflects as well the range of overvoltages from the point of view of timing. The tested devices from Hamamatsu are typically operational up to 5 V overvoltage. Most other devices operate optimally until an overvoltage of around 10 V with the exception of FBK NUVHD which operates until 18 V, which is the highest overvoltage among all the devices. The extremely high overvoltage along with a low dark count rate results in a low measured time resolution even for a larger device of \(4 \times 4 \text{mm}^2\) (larger when compared to the other measured devices). SiPM from STMicroelectronics also results in a low value of the measured time resolution despite its size. We measured larger time resolution values for Ketek devices in comparison with the FBK and Hamamatsu devices.
Influence of area Systematic measurements on FBK (Red Green Blue) SiPMs starting from the level of a stand-alone single SPAD to a 3 × 3 mm$^2$ SiPM were performed by Acerbi et al., [16], where they concluded that the degradation of SPTR with increasing device area is due to the effect of capacitance on the rising edge (lower $\frac{dV}{dt}$), and a higher baseline noise due to a higher DCR, afterpulsing and crosstalk. We verified this effect for two cases; the Hamamatsu TSV and the FBK NUV where devices with the same technology and different areas were compared. Figure 6 shows the SPTR as a function of overvoltage for different devices of Hamamatsu TSV technology (left) and FBK NUV technology (right). As it can be observed, the SPTR improves with a decreasing device area. The difference in the measured SPTR at similar overvoltages is especially significant.

To summarize the results of SPTR along with the measurements on capacitance and the detector noise, we present these values in table 2. All the values from table 2 correspond to the same settings for a given SiPM. The measured values of the first order crosstalk and the DCR for various devices are also listed in table 2. Crosstalk values were determined by taking a ratio of the areas of the
Table 2. List of optimum values of measured SPTR with diffuse laser illumination and the values of the device capacitance measured for the same applied voltage. Also listed are the values of the crosstalk (labeled CT) and dark count rate (labeled DCR) measured at the same overvoltage as for the SPTR value stated.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>Device area (mm$^2$)</th>
<th>Cell size ($\mu$m)</th>
<th>Capacitance (pF)</th>
<th>SPTR FWHM (V)</th>
<th>Overvoltage (V)</th>
<th>CT (%)</th>
<th>DCR (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM</td>
<td>4.3 × 3.6</td>
<td>50</td>
<td>1250</td>
<td>200 ± 8</td>
<td>9.2</td>
<td>28</td>
<td>40</td>
</tr>
<tr>
<td>FBK NUVHD</td>
<td>4 × 4</td>
<td>25</td>
<td>610</td>
<td>205 ± 7</td>
<td>16.2</td>
<td>57</td>
<td>5.5</td>
</tr>
<tr>
<td>FBK NUV</td>
<td>3 × 3</td>
<td>40</td>
<td>440</td>
<td>175 ± 7</td>
<td>8.3</td>
<td>40</td>
<td>1.2</td>
</tr>
<tr>
<td>FBK NUV</td>
<td>1 × 1</td>
<td>40</td>
<td>55</td>
<td>94 ± 5</td>
<td>9.3</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>FBK NUV</td>
<td>SingleCell</td>
<td>40</td>
<td>-</td>
<td>75 ± 4</td>
<td>15.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ham TSV</td>
<td>3 × 3</td>
<td>50</td>
<td>315</td>
<td>290 ± 7</td>
<td>2.6</td>
<td>34</td>
<td>0.6</td>
</tr>
<tr>
<td>Ham TSV</td>
<td>2 × 2</td>
<td>50</td>
<td>154</td>
<td>215 ± 5</td>
<td>3.4</td>
<td>30</td>
<td>0.8</td>
</tr>
<tr>
<td>Ham LCT2</td>
<td>3 × 3</td>
<td>50</td>
<td>340</td>
<td>220 ± 7</td>
<td>6.1</td>
<td>38</td>
<td>1.0</td>
</tr>
<tr>
<td>SensL JD0</td>
<td>3 × 3</td>
<td>35</td>
<td>790</td>
<td>290 ± 7</td>
<td>8.7</td>
<td>32</td>
<td>0.9</td>
</tr>
<tr>
<td>SensL JD4</td>
<td>3 × 3</td>
<td>20</td>
<td>690</td>
<td>270 ± 7</td>
<td>6.9</td>
<td>16</td>
<td>0.8</td>
</tr>
<tr>
<td>Ketek Optimized</td>
<td>3 × 3</td>
<td>50</td>
<td>820</td>
<td>330 ± 7</td>
<td>5.2</td>
<td>20</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The timing jitter of the individual SPAD itself is a contributor to the overall timing resolution of the SiPM. In order to understand the influence of the photon injection position on the timing jitter on a single photon avalanche diode, Assanelli et al., [20] performed timing measurements by focusing a laser on a single SPAD, and concluded that the photon injection and the specific resistance are the two factors that affect the timing jitter. In that study the specific resistance is reported to contribute to a lower jitter at the border regions albeit at higher thresholds. In this study we work entirely with SiPMs and the values reported in section 4.2 are for optimized threshold values at the best bias overvoltage. Hence we limit ourselves to the position dependent measurements of the SPTR within a SPAD of the SiPM.

4 Contributions from the SPAD

In order to better understand the timing performance of the devices, we investigated the effect of focusing the laser light to the level of a SPAD within a SiPM. Various factors such as the non-uniformity of the SPTR among different SPADs within a SiPM, the spread in the signal transit time from different SPADs etc could degrade the SPTR in principle from a diffuse illumination to a focused illumination. The extent to which these factors degrade the timing resolution are investigate in sections 4.1 and 4.2.

The timing jitter of the individual SPAD itself is a contributor to the overall timing resolution of the SiPM. In order to understand the influence of the photon injection position on the timing jitter on a single photon avalanche diode, Assanelli et al., [20] performed timing measurements by focusing a laser on a single SPAD, and concluded that the photon injection and the specific resistance are the two factors that affect the timing jitter. In that study the specific resistance is reported to contribute to a lower jitter at the border regions albeit at higher thresholds. In this study we work entirely with SiPMs and the values reported in section 4.2 are for optimized threshold values at the best bias overvoltage. Hence we limit ourselves to the position dependent measurements of the SPTR within a SPAD of the SiPM.

4.1 Focused SPTR measurement

Experimental setup for measuring the focused SPTR has been presented in section 2.5. Before proceeding to measure the focused SPTR for different samples it is necessary to verify the uniformity of SPTR along different points within the SiPM. To check this we measured the focused SPTR with
laser incident on different points of a SiPM for one sample - Hamamatsu TSV $2 \times 2 \text{mm}^2$. For the chosen SiPM, the measured region corresponds to one quadrant of the entire area where a vertical and a horizontal scan along a line were performed to chart the selected region. The TSV is present in the top right region of the scanned area around [169.85 mm, 137.9 mm]. The result, as seen in figure 7 shows that there is a statistical variation of $\pm 5 \text{ ps } \sigma$ about a SPTR mean value of 175 ps among the measured points. The values of delay that are also printed in figure 7 show a greater variation. The reason for variation is the non-uniformity of the delay within a SPAD of a SiPM and will be explained in a greater detail in section 4.2.

**Figure 7.** A map of the SPTR measured at different positions of the SiPM Hamamatsu TSV $2 \times 2 \text{mm}^2$ using a focused laser. SPTR values are printed into red boxes corresponding to each point on the SiPM. This plot illustrates the uniformity of SPTR at different points within a SiPM. The mean delay values are also printed in the blue boxes for reference.

The uniformity of SPTR among different SPADs was independently confirmed for FBK SiPMs in [16]. Based on these results we make a reasonable assumption that the SPTR among various SPADs within the SiPM for the tested samples will be uniform. However we have not verified this for each individual sample. For all subsequent cases we measured the focused SPTR for the SiPM samples for an arbitrarily chosen SPAD in the middle.

In order to determine the value of focused SPTR, we performed a scan of the SPTR values also in the neighboring SPADs to ensure that the value is stable. Figure 8 shows the values of the measured focused SPTR for the best settings for various devices in comparison with the diffuse measurements. Lines have been drawn between the points to serve as an eye guide. As seen in this figure the focused SPTR values are lower than the diffuse values for all the devices. In addition, we measured the timing values with a higher photon flux while staying focused at a SPAD level which is shown in figure 8 and table 3. When the single p.e spectrum has a dominant single peak with a significantly smaller 0 p.e peak, it is a confirmation that there are multiple photons incident on a single SPAD as seen in figure 9 (right). In this way we ensured that the resulting signal was due to a single SPAD that was being triggered by multiple photons. The Poisson mean computed from the single p.e spectrum showed that at least three photons were being incident on a single cell. A higher number of photons incident on the same SPAD improves the timing due to two factors - (1)
Figure 8. Measured values of SPTR for various devices. The red and blue colored points respectively represent the cases of focused and diffused SPTR. The green colored points represent the timing values measured with a focused laser at a high intensity.

Figure 9. Single p.e spectrum for Hamamatsu TSV $2 \times 2 \text{mm}^2$ measured with laser light focused on to a single SPAD. Left: laser light incident at a single photon rate. The peaks corresponding to 2 p.e and higher are due to crosstalk as confirmed by the ratio of the areas of the 2p.e peak to the 1p.e peak which is equal to 30%. Right: laser light incident at a multi photon rate. Single p.e peak is dominant as multiple photons trigger the same SPAD. The ratio of the areas of the 2p.e peak to the 1p.e peak equal to 30% similar to the single photon rate from the left figure and is due to crosstalk.

reduced inherent contribution of the laser width of 42 ps FWHM, (2) reduced jitter in the avalanche generation at a SPAD level. The improvement in the timing due to multiple photons, obtained by subtracting the two values in quadrature is of the order of 40 ps FWHM in most of the cases and is hence mostly dominated by the laser jitter (see table 3).

4.2 SPAD jitter and transit time spread

We performed a scan of the SPTR with focused light at different points within a given SPAD of the SiPM for two different samples - Hamamatsu TSV $2 \times 2 \text{mm}^2$ and NUV $3 \times 3 \text{mm}^2$. The objective of such a measurement was to determine the non uniformity of the SPTR at a SPAD level. By
Table 3. Comparison of the timing performance under various conditions of focused photon incidence for different devices. The second column reports the value of SPTR while the third column is the measured timing jitter when multiple photons from the laser are focussed on to a single SPAD.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>SPTR focused (ps)</th>
<th>Timing resolution focused multi photon (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STM</td>
<td>175 ± 7</td>
<td>168 ± 7</td>
</tr>
<tr>
<td>NUVHD</td>
<td>180 ± 6</td>
<td>-</td>
</tr>
<tr>
<td>NUV</td>
<td>150 ± 6</td>
<td>135 ± 5</td>
</tr>
<tr>
<td>Hamamatsu TSV3x3</td>
<td>226 ± 6</td>
<td>220 ± 6</td>
</tr>
<tr>
<td>Hamamatsu TSV2x2</td>
<td>182 ± 4</td>
<td>175 ± 4</td>
</tr>
<tr>
<td>Hamamatsu LCT2</td>
<td>170 ± 5</td>
<td>145 ± 5</td>
</tr>
<tr>
<td>SensL JD0</td>
<td>264 ± 7</td>
<td>247 ± 6</td>
</tr>
<tr>
<td>SensL JD4</td>
<td>227 ± 7</td>
<td>220 ± 6</td>
</tr>
<tr>
<td>Ketek Optimized</td>
<td>210 ± 4</td>
<td>200 ± 4</td>
</tr>
</tbody>
</table>

analyzing the single p.e spectra we also determined a map of the relative PDE at various points with respect to the center of the SPAD. We found that both the relative PDE and the SPTR vary within a SPAD at different locations; the best values being obtained at the center of the SPAD. A general degradation was also observed towards the edges as seen in figures 10 and 11.

Figure 10. Left: SPTR map at a SPAD level measured with focused light for the FBK NUV SiPM 3 x 3 mm$^2$ measured at the best settings of 8.3 V overvoltage and 60 mV NINO threshold. Right: map of the relative PDE at a SPAD level of FBK NUV SiPM 3 x 3 mm$^2$ measured with focused light for the same settings.

The mean value of the signal delay also varies with position. Figure 12 shows the scatter plots of Delay vs relative PDE (left) and SPTR vs relative PDE (right) at the level of a SPAD for both the measured SiPMs. The variation in the SPTR and the mean delay values with the relative PDE implies that a degradation can be expected when light is incident on the entire SPAD in relation to the center of the SPAD. For a given change in the relative PDE it can also be seen from figure 12 that the variation of the delay is higher than that of the SPTR. This explains also the observed variation in the delay values measured at various positions as a part of the measurement to
Figure 11. Left: SPTR map at a SPAD level measured with focused light for the Hamamatsu TSV SiPM 2 × 2 mm² measured at the best settings of 4 V overvoltage and 110 mV NINO threshold. Right: map of the relative PDE at a SPAD level of Hamamatsu TSV SiPM 2 × 2 mm² measured with focused light for the same settings.

Figure 12. Left: scatter plot of pulse delay vs relative PDE measured using a focused laser incident at different positions within a SPAD of a SiPM for the two samples Hamamatsu TSV 2 × 2 mm² and FBK NUV 3 × 3 mm². Right: scatter plot of SPTR vs relative PDE for the same measurement.

determine the uniformity of the SPTR among various SPADs within a SiPM as seen in figure 7. In that measurement if a given SPAD is illuminated at a point further away from the center, a variation in delay is bound to occur. In order to determine the center for a single SPAD within an SiPM for the focused measurement, a relative PDE map of the entire cell along with its neighbourhood is made. Such level of precision with respect to finding the center of a SPAD was not necessary in the case of SPTR uniformity measurement and hence it should be noted that the delay values from figure 7 do not convey any information concerning the signal transit time.

When the time delay histograms measured at different points within a SPAD in a SiPM are summed up, the width of the fit function to the cumulative histogram yields the effective SPTR value of the SPAD. The summed histogram is seen in figure 13 for each of the two measured SiPMs. Measurements for each individual point are performed for the same amount of time, hence, the lower relative PDE regions contribute lesser data points in comparison with regions having a high relative PDE.
The cumulative SPTR for the entire SPAD was estimated to be 217 ± 5 ps for Hamamatsu TSV (2 × 2 mm²) and 164 ± 4 ps for NUV (3 × 3 mm²) SiPM. These values are close to the SPTR measured on the respective SiPMs with light diffused over the entire area. This measurement shows that the dominant contribution to the degradation from a focussed SPTR to the diffuse SPTR comes from the non-uniformity of the relative PDE, SPTR and the delay at a SPAD level. A slightly bigger difference in the values of the diffuse and the cumulative SPTR for FBK NUV (3 × 3 mm²) in comparison with the Hamamatsu TSV 2 × 2 mm² SiPM as seen in table 4 can be due to a larger contribution of the signal transit time spread for the larger device. The value of the delay time spread of FBK NUV device can be estimated by taking a difference in quadrature the two values 175 ps (diffuse SPTR) and 165 ps (SPTR SPAD cumulative). This value is 58 ± 7 ps. Following this observation, we can expect to see a larger contribution of transit time spread for larger devices. The presence of optimized contact points for signal collection serves to reduce its effect and has been implemented in the optimized versions of some of the devices.

Table 4. SPTR measured for Hamamatsu TSV 2 × 2 mm² and FBK NUV 3 × 3 mm² SiPMs in various ways are presented for comparison. The diffuse laser measurement is the highest value and the focused laser measurement is the lowest value. The cumulative SPTR seen in the third column shows the contribution from the entire SPAD.

<table>
<thead>
<tr>
<th>SiPM</th>
<th>SPTR diffuse (ps)</th>
<th>SPTR focussed (ps)</th>
<th>SPTR SPAD cumulative (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hamamatsu TSV</td>
<td>215 ± 5</td>
<td>182 ± 4</td>
<td>217 ± 5</td>
</tr>
<tr>
<td>FBK NUV</td>
<td>175 ± 7</td>
<td>150 ± 6</td>
<td>164 ± 4</td>
</tr>
</tbody>
</table>
5 Stand-alone single SPADs and the limits of the timing performance

In this section we present some of the measurements on stand-alone single SPADs that were produced by FBK. These measurements serve as a source of understanding the limits of the timing performance of SPADs because the contributions arising from signal transit time spread and the influence of capacitance, dark counts, afterpulse and crosstalk due to multiple SPADs is discounted. All the SPADs belong to the NUV technology with each of them having a different size of the photosensitive area. The $40 \mu m^2$ SPAD is comparable to the SPADs from the NUV SiPM and some measurements were already shown in figure 6 on the right hand side. The $30 \mu m$ and $10 \mu m$ SPADs are circular and result from masking the conventional SPAD and for this reason cannot strictly be compared to the SPADs in the NUV SiPM. The circular SPADs that have a metallization layer have a higher signal and a better timing jitter as presented in [21] and are somehow comparable to focused laser measurements on normal SPADs.

We performed single photon measurements by ensuring that the 0 p.e is the dominant peak in the spectrum which has only 0 p.e and 1 p.e. The incident light was diffused on to the entire SPAD. The plot shown in figure 14 (left) shows the discriminating threshold dependence of the SPTR. Best measured values are around 52 ps FWHM for the $10 \mu m$ and $30 \mu m$ SPADs while the $40 \mu m$ SPAD has a slightly worse value of 73 ps FWHM. It is important to note that these values include two contributions in addition to the SPAD jitter, namely electronic noise, acquisition jitter (oscilloscope, see section 2.3) and the laser jitter. The laser pulse has a finite width of 42 ps FWHM which was measured using a streak camera. This value is corrected for the contribution of streak camera time resolution having a value of 18 ps FWHM. The acquisition jitter was measured to be ~ 21 ps FWHM. These values degrade the measurement and have to be removed in order to estimate the intrinsic SPTR of the devices. Removing the two contribution the $10 \mu m$ and $30 \mu m$ SPAD show SPTR values close to 20 ps FWHM. Figure 14 (right) shows the measured timing performance with a high intensity of laser light impinging on the SPAD. This measurement removes the contributions due to laser jitter and the SPAD jitter leaving the electronic noise and acquisition influence which is of the order of 25–30 ps FWHM for all the SPADs.

![Figure 14](image.png)

Figure 14. Measured single photon time resolution values as a function of the discriminating threshold voltage for different stand-alone single-SPADs fabricated by FBK with the NUV technology. Left: laser light is incident at a strictly single photon rate. Right: laser intensity is kept at a maximum to have multiple photon incidences for every event.
6 Conclusion

SiPMs fabricated by various producers have different optimal values of SPTR falling in the range of 175 ps–330 ps FWHM. The variation in the measured SPTR values among different devices can be due to various factors such as device capacitance, dark counts, after pulse, crosstalk, signal transit time spread and the SPAD jitter.

SPTR measurements with focused laser indicate that there is an observable improvement in the value from diffuse illumination on a SiPM to focused illumination (with single photons incident on a single SPAD) on a SiPM. A further improvement in the timing resolution was observed with multi-photons incident on a single SPAD of a SiPM. Such improvements were seen for all the measured SiPMs and are partially due to the reduced contribution of the laser jitter.

The dominant contribution to the worsening of the SPTR measured with diffuse laser in comparison with the focused laser is the non-uniformity of the SPTR, the signal mean delay and the relative PDE within a SPAD belonging to a SiPM. The timing performance of the SiPMs is better when the light is detected in the central regions of the SPADs when compared to the edges. This result can be useful to modify the SiPMs to optimize the timing performance. In case of digital SiPMs for e.g., it might be possible to sacrifice the active area at the edges of the SPAD to implement electronics (TDC) while still retaining a superior timing performance. The two devices Hamamatsu $2 \times 2$ mm$^2$ and FBK-NUV $3 \times 3$ mm$^2$ for which the transit time spread was estimated through intra-SPAD SPTR measurements with focused laser showed that the contribution is not significant at the achieved SPTR levels at this time.

We also found through focused laser measurements that the relative PDE changes with the photon incidence position on a SPAD within a SiPM. The best detection efficiency being in the middle of the SPAD. An inverse relationship between the SPTR and the relative PDE was observed at different positions within a given SPAD of a SiPM. Measurements of SPTR in relation to capacitance show that a degradation of the values is observed for larger devices that likely results from a lower signal slope and a higher detector noise.

Stand-alone single SPADs produced by FBK with NUV technology point towards the limits in the achievable timing resolution. When all external contributions such as electronic noise and the laser jitter are removed from the SPTR of stand-alone single SPADs of FBK-NUV, the resulting values are close to 20 ps FWHM. We infer from our measurements that the most significant factor contributing to the degradation of the SPTR from the level of a SPAD to a SiPM is the detector noise.

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