Application Note

AFBR-S4NXX

SiPM Waveform and Bandwidth Consideration

Version 1.0

Overview

SiPM are employed in numerous applications with each imposing dedicated requirements on the sensor and its signal.

Hence, the design for an appropriate readout design requires in-depth considerations of the full readout chain rather than only individual components.

This application note provides details on how the choice of SiPM active area and load resistor affect the signal shape by changing the bandwidth of the SiPM signal.

Material and Methods

SiPM

Measurements presented in this application note were performed on Broadcom NUV-MT SiPM soldered to an interposer PCB with pin headers. The devices under investigation were:

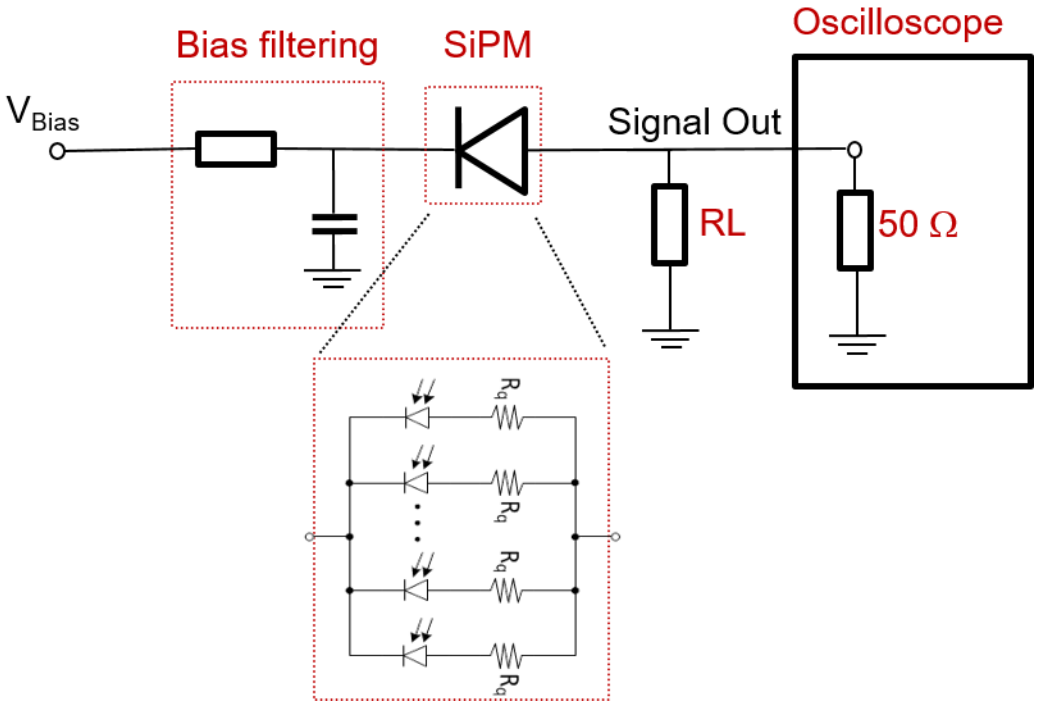
- Test SiPM with 1 x 1 mm² active area
- AFBR-S4N22P014M with 2 x 2 mm² active area
- AFBR-S4N44P014M with 3.7 x 3.6 mm² active area
- AFBR-S4N66P014M with 6 x 6 mm² active area

The SiPM is operated at 12 V_{OV}.

Readout

The SiPM interposer is inserted on a DC readout PCB (Figure 1). The SiPM bias was applied to the Cathode and a simple RC bias filtering is used to reduce ripple noise form the power supply. The SiPM signal is extracted form the Anode. The load resistor R_L is optional. The signal acquisition is done using an oscilloscope with 2.1 GHz maximum bandwidth. The oscilloscope input impedance is set to 50Ω. If a 50Ω R_L is equipped on the readout PCB, the effective load is 25Ω, otherwise 50Ω. On the oscilloscope a software bandwidth limit can be set, which allows to investigate the signal at various bandwidth limitations.

Figure 1: Schematic and Pictures of the DC Readout PCB



Signal Acquisition and Analysis

The waveforms used for the analysis were acquired under dark conditions, that means they represent dark counts. On the acquired segments, an amplitude filter is applied to select the single photo-electron pulses (SPE). Furthermore, additional filters to eliminate segments containing afterpulses or additional pulses is applied. An averaging routine is subsequently applied to obtain an averaged pulse of several hundred single pulses. The averaging allows effective elimination of electronic noise and increases the prominence of the pulse.

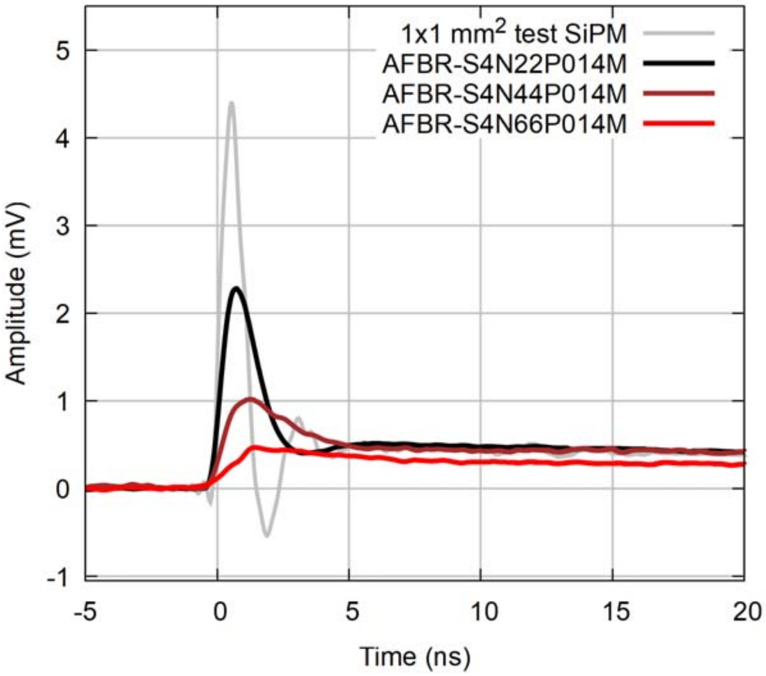
Load Resistor and Grid Capacitance

The SiPM grid C_g (metal connections between the individual SPADs) add parasitic capacitances to the readout line. The parasitic capacitance forms a RC low-pass filter together with an external load resistor.

The values of R_L and C_g determine the cut-off frequency of the readout and, therefore, limit the maximum achievable signal bandwidth.

The SiPM signal is (in first order) composed of two components contributing to the signal's falling edge. The low-pass upper frequency limit mainly affects the fast signal component. A comparison between the signal shapes of SiPM with different active area but same technology (and therefore same gain) clearly demonstrates this fact (Figure 2).

Figure 2: Zoom in the first 20 ns of the single waveforms of four SiPM with active areas between 1 x 1 mm^2 and 6 x 6 mm^2



The pulses shown in Figure 2 were acquired with an effective load of 25Ω and therefore only reflect the cut-off frequency shift due to the grid capacitance.

The bandwidth limitation demonstrates two effects.

1. The signal amplitude decreases: The high signal frequencies are filtered which effectively reduces the signal amplitude. As the overall charge is conserved, the charge carriers become part of the slow signal component. Hence, the *back-to-baseline* time prolongs for the low-pass filtered signals. Figure 5 shows the slow component of the AFBR-S4N66P014M crossing the signals of the other two SiPMs and taking longer to return to baseline.
2. The signal rise time increases: Figure 2 demonstrates that the signal of the 1x1 mm^2 SiPM has already decreased to 10% at the time of the maximum of the signal of the AFBR-S4N66P014M.

As a consequence of these two effects, the signal's slew rate decreases.

Another effect which becomes only visible if the signal bandwidth is very high is influences of (parasitic) inductances in the signal readout chain. These inductances causes the signal to oscillate. For the e1 x 1 mm^2 test SiPM, the fast signal component and the bandwidth, both are high enough for this phenomenon to become visible by an undershoot (with signal polarity inversion) in Figure 2. For the 2 x 2 mm^2 SiPM a dip between the fast and the slow signal component is visible but the overall signal is already too slow as to show a full undershoot.

The second parameter which can change the cut-off frequency of the low-pass filter is the load resistor R_L. However, when measuring the SiPM's current signal as voltage signal over a load resistor (transimpedance), the voltage swing will depend on the resistor value (Ohm's law). If the cut-off frequency change caused by changing the load resistor's value is in a frequency domain much higher than the SiPM's frequency, the signal amplitude will change accordingly. That means increasing the resistor by a factor of two will also increase the voltage swing by a factor of two. However, in most cases, the cut-off frequency of the low-pass is in the same region as the SiPM's frequency and, therefore, the cut-off frequency will impact the signal shape and amplitude. Figure 3 shows the single photon waveform of a 2 x 2 mm^2 SiPM (AFBR-S4N22P014M) readout over 25Ω (black) and 50Ω (red). For this SiPM with a small grid capacitance, increasing the load resistor from 25Ω to 50Ω will strongly suppress the fast signal component resulting in a smaller signal amplitude. The slow signal component, on the other side, is less prone to frequency changes in the several hundred MHz region and increases in amplitude.

In contrast to the 2 x 2 mm^2 SiPM, the grid capacitance of the 4 x 4 mm^2 SiPM is large which results in an overall reduced bandwidth. Here, the signal amplitude of the one photo-electron signal is higher (fast and slow component) when using 50Ω compared to 25Ω to convert the current pulse to a voltage signal (Figure 4).

Figure 3: Averaged Single Photon Waveform AFBR-S4N22P014M

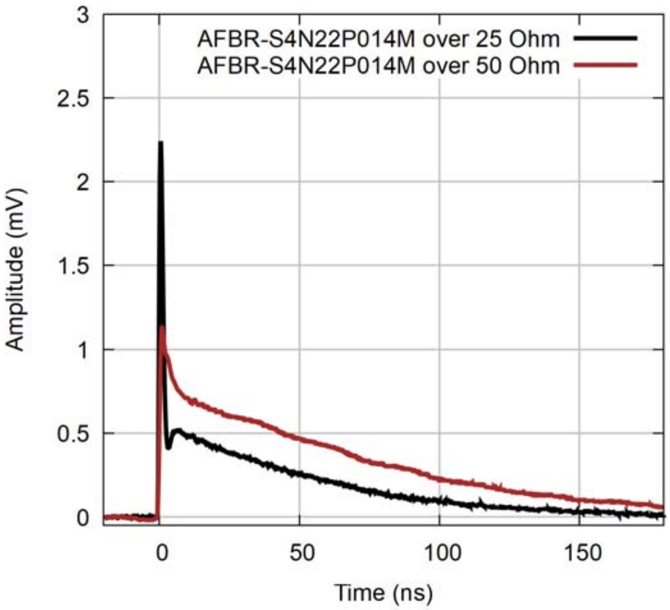
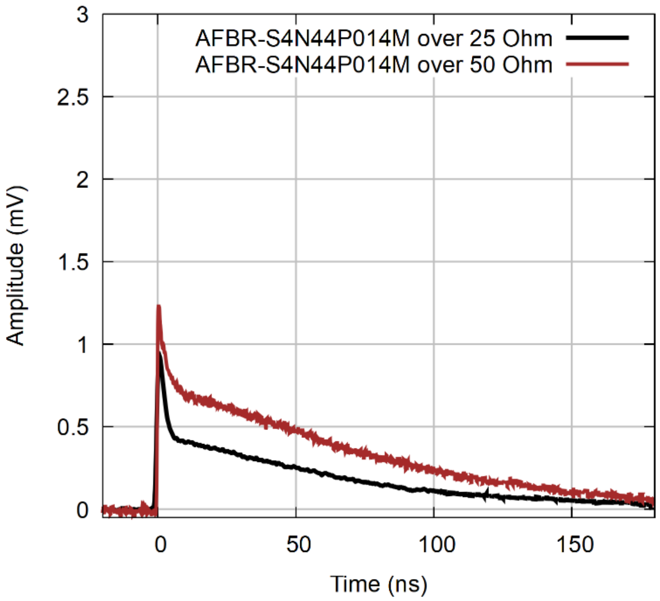


Figure 4: Averaged Single Photon Waveform AFBR-S4N44P014M



Signal and Bandwidth

As discussed in Load Resistor and Grid Capacitance, the single photon response of Broadcom's NUV-MT SiPM (AFBR-S4N Series) depends on the active area (even if all other parameters are similar). A comparison of the single photo-electron (SPE) waveforms is displayed in Figure 5 and a zoom in of the first 20 ns of the signal is displayed in Figure 6.

The average waveforms allow to numerically determine the SPE amplitude for the three devices and the rise time. Table 1 summarizes both parameters.

Figure 5: SPE Pulse (over 25Ω)

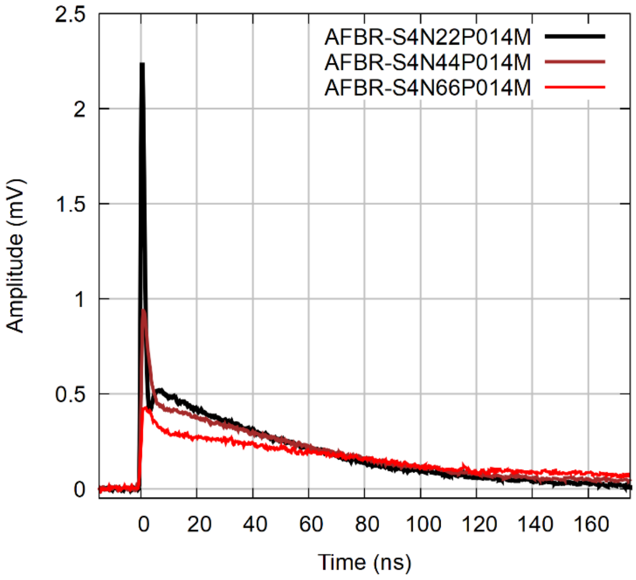


Figure 6: First 20 ns of SPE Pulse (over 25Ω)

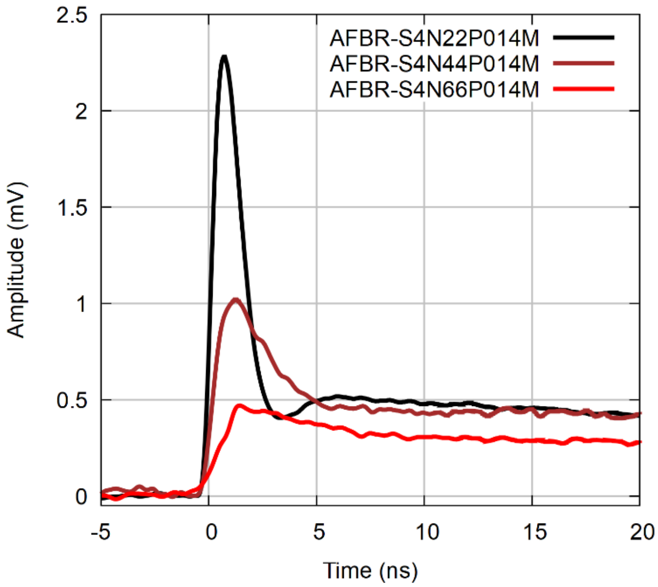


Table 1: Summary of the SPE Amplitude and Signal Rise Time

SiPM	SPE Amplitude [mV]	Rise Time (20%/80%) [ps]	Rise Time (Full) [ps]
AFBR-S4N22P014M	2.3	440	1110
AFBR-S4N44P014M	0.9	600	1450
AFBR-S4N66P014M	0.45	1100	2550

With the much higher amplitude of the fast component of the AFBR-S4N22P014M compared to the larger SiPM, the expectation is that the overall signal bandwidth is also higher, which can be verified by looking at the Fourier transformation of the averaged SPE waveforms (Figure 7).

For applications in which the timestamps are taken (for examples when the signal amplitude exceeds a pre-defined threshold), the bandwidth is ideally set such that it does not limit the SiPM's rising edge. The ideal bandwidth setting for the three devices is difficult to determine from Figure 7.

Alternatively, the SPE waveforms of the three devices are measured at different bandwidth settings on the oscilloscope. Starting at a high bandwidth (1 GHz) and systematically reducing the bandwidth in small steps, a setting can be found at which the signal amplitude starts to decrease. The corresponding bandwidth setting provides a good estimate for the maximum needed electronics bandwidth setting to maximize timing accuracy for a given device[1]. Figure 8, Figure 9, and Figure 10 show the measured and averaged SPE waveforms of the 2 x 2 mm^2, the 4 x 4 mm^2 and the 6 x 6 mm^2 SiPM at various oscilloscope bandwidth values.

A comparison between the three plots validates the finding of Figure 7 which is that the smallest device (AFBR-S4N22P014M) has the highest frequency components in it's waveforms. Furthermore, it becomes evident that the slow signal component's frequency content is below 100 MHz as its amplitude remains constant throughout the bandwidth sweep.

From Figure 8, it can be derived that the AFBR-S4N22P014M signals contains frequencies up to about 650 MHz. For the AFBR-S4N44P014M (Figure 9), signal frequencies reach up to 450 MHz and up to 200 MHz for the AFBR-S4N66P014M (Figure 10).

Figure 7: Fourier Transformation of Averaged SPE Signals

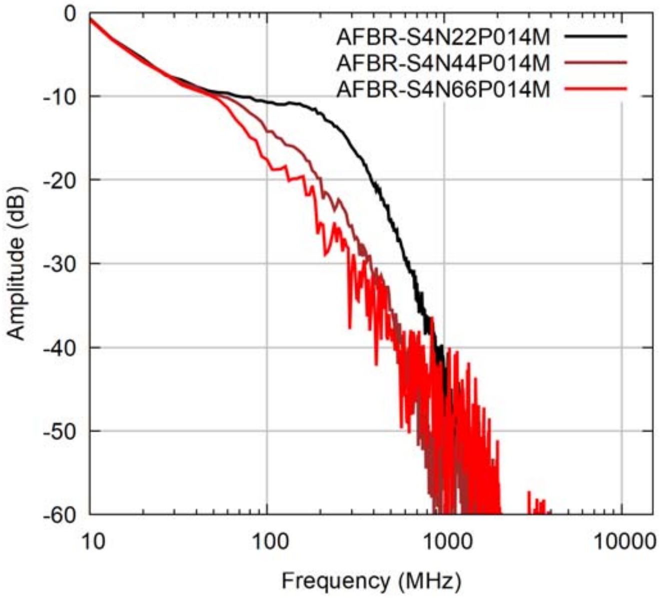
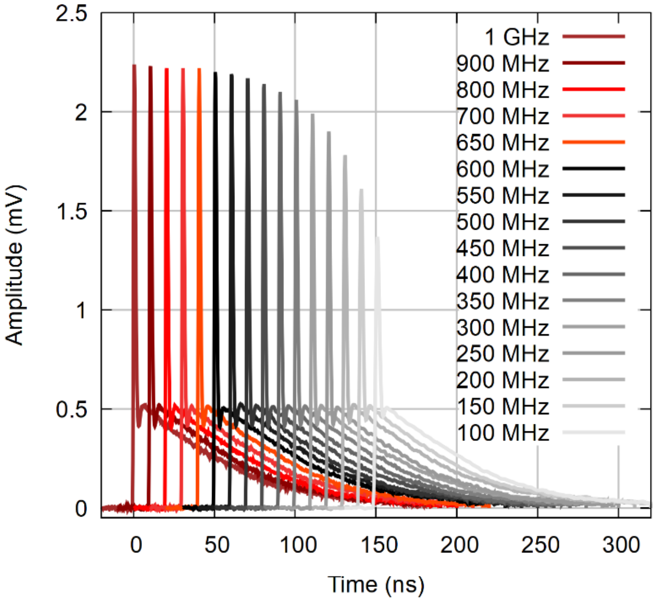


Figure 8: SPE Waveform of the AFBR-S4N22P014M Measured at Decreasing Bandwidths



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[1] For best timing accuracy not only the slew rate is a crucial parameter. The overall noise of the baseline can have significant influence on the expected result. In such cases, limiting the bandwidth further can result in positive results on the timing accuracy.

Figure 9: SPE Waveform of the AFBR-S4N44P014M Measured at Decreasing Bandwidths

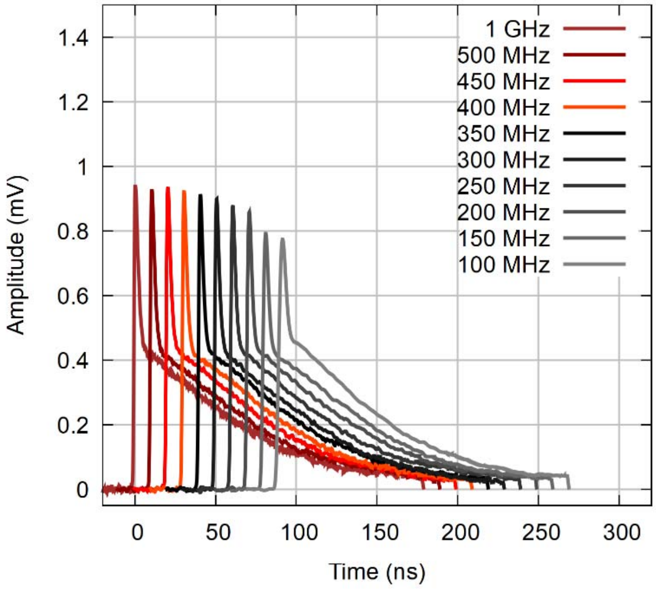
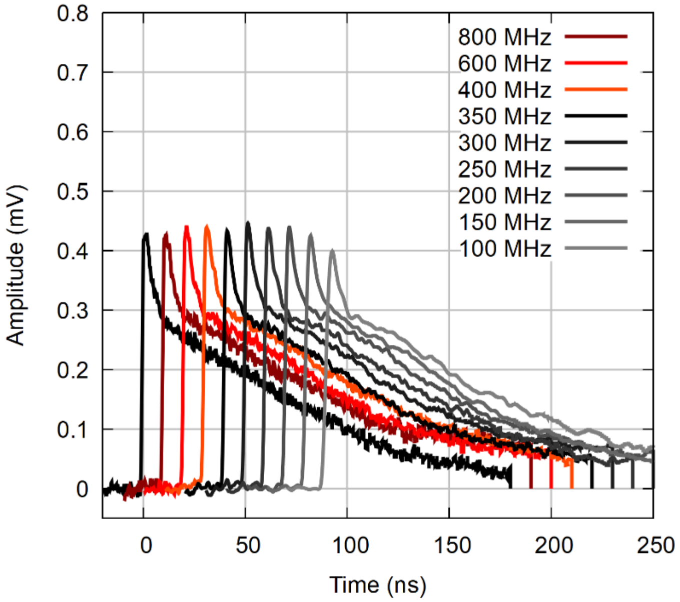


Figure 10: SPE Waveform of the AFBR-S4N66P014M Measured at Decreasing Bandwidths



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