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Avalanche dynamics in silicon avalanche single- and few-photon sensitive photodiode

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Abstract. We are presenting the results of the study of the Single Photon Avalanche Diode (SPAD) avalanche pulse response rise-time and its dependence on several key parameters. We were investigating the unique properties of K14 type SPAD with its high delay uniformity of 200 μm active area, the character of avalanche, and the correlation between the avalanche build-up time and the photon number involved in the avalanche trigger. The detection chip was operated with bias higher than breakdown voltage, i.e. in Geiger mode. The detection chip was operated in a passive quenching circuit with active gating. This set-up enabled us to monitor both the diode reverse current using an electrometer and a fast digitizing oscilloscope. The electrometer reading enabled to estimate the photon number per detection event, the avalanche build up was recorded on the oscilloscope and processed by custom designed waveform analysis package. The correlation of avalanche build up to the photon number, bias above break, photon absorption location, optical pulse length and photon energy was investigated in detail. The experimental results are presented.

1. Introduction
The single photon sensitive avalanche photodiodes acting as photon counting devices has been pioneered by Sergio Cova and co-workers [1]. This detector, called Single Photon Avalanche Diode (SPAD), is an avalanche photodiode structure prepared using a conventional planar technology on silicon. Single photon sensitivity is achieved by biasing the diode above the junction breakdown voltage. In this metastable stage the first absorbed photon is capable of triggering the avalanche multiplication of carriers; a fast rise-time current pulse is generated. The leading edge of the current pulse marks the event of the photon absorption with picosecond accuracy. The current increase is terminated by an external circuit connected to the diode, where the typical value of the gain achieved exceeds 1×10^7. Such an operation mode is called a Geiger mode in analogy with nuclear technique. The operation of the detector may be controlled – gated, by an external electrical signal.

In our experiments we have concentrated on the operation of the SPAD diodes in the regime of detecting single or several photons per pulse. The existing solid state photon counting detectors have been dedicated for high timing resolution and stability of single photon events. However, the high timing stability is maintained for individual single photons detection, only [2]. If more than one photon is absorbed within the detector time resolution, the detection delay will be significantly affected. This fact is restricting the application of the solid state photon counters to cases where single photons may be guaranteed in principle. The example of such an application is the time resolved spectroscopy, single molecules detection and similar. However, there is a demand for detection of
optical pulses consisting of several up to several thousands of photons with picosecond resolution and stability. No conventional optical detector or photon counter can fulfill these requirements. The standard SPAD based photon counters work in a purely digital mode - uniform output signal is generated once a photon is detected. If the input signal consists of several photons, the first absorbed one triggers the avalanche. For multiple photon signals, the detection delay will be shorter in comparison to the single photon events. The detection delay dependence on the photon number is called the “detection time walk”. To enable the detector operation in both the single and multi-photon signal regime with a minimal time walk, a time walk compensation technique has been developed [3] in nineties. The operation of this device was based on unique properties of the K14 SPAD detectors [4]. The procedure is based on the fact that the avalanche rise-time of the K14 SPAD chip is depending on the input optical signal strength. The circuit is using this information to compensate the time walk of the detector in this dynamical range.

2. Experiment
The SPAD chips were tested and operated in an active gated and passively quenched circuit. The scheme enables to bias the chip to the voltage on just below its breakdown voltage. The SPAD bias is increased for a short time (100 ns typically) for additional step of the negative gate pulse.

The picosecond laser diode Hamamatsu C4725 providing 42 ps wide pulses at 778 nm was used as a signal source. The laser output was attenuated by means of a stack of calibrated neutral density filters and focused on the detector active area. The precision X-Y-Z stage enabled us to investigate focusing and position sensitive effects of the detection process. The optical signal intensity was measured using the detection chip in a linear mode with unity gain and monitoring its reverse current by the electrometer Keithley 610C and operating the power stabilized laser source at a high repetition rate of 1 MHz.

The detector was operated in an active gated and passive quenched circuit; its pulse output was monitored on the digital oscilloscope LeCroy SDA 9000 with the 9 GHz analogue bandwidth and 40 Gs/s sampling frequency. The individual current rise-time waveforms were recorded with a resolution of 40 Gs/s and processed off-line using a custom software package. Independent measurement series were completed in the configurations of optical signal either focused to the active area center or illuminating the entire sensitive area.

3. Results and conclusion
At first, the “thick” SPAD C-30902S manufactured by Perkin Elmer (formerly RCA) was investigated. The breakdown voltage is 238 Volts. This relatively slow structure allows clearly see the difference in avalanche temporal profile. Examples of the response to a single photon are recorded in figure 1 together with the response to the short optical pulse consisting of 3000 and 10 thousands photons. The chip was pulse biased 5 Volts above its breakdown voltage. Different avalanche buildup shape – pulse fall times is apparent.

The last avalanche photodiode chip under test was the K14 structure made by our University. This is the “thin” SPAD structure on silicon, the active area diameter is with 200 μm. The K14 type SPADs are characterized by several special features in comparison to other SPADs. It is the exceptionally high active area uniformity in both the timing jitter and mainly of the detection delay over an entire sensitive area. In the series of experiments, the input signal strength was adjusted using calibrated neutral density filters to the values 1, 3, 10,… up to 10 000 photons per event. The avalanche current response pulses were recorded, stored and off-line processed using the custom designed software package. The times when the avalanche current exceeded the pre-selected level were evaluated. The results are summarized in figure 2. The difference between detection delay related to the trigger level of 10 mV are plotted for two different optical configurations. In the first configuration the detected photons were absorbed within a small area close to the sensitive area center. In the second configuration the detected photons were absorbed uniformly over the active area. The error in vertical
axis are plotted, in horizontal axis the data are blurred by the photon counting statistics – Poisson distribution of attenuated laser light.

Figure 1. The oscillogram of the response of the C-30902s SPAD to single, 3000, and 10000 photon level.

Figure 2. The detection delay for various photon numbers, K14 SPAD biased 5 V above breakdown voltage, optical pulses 48 ps long, trigger level 10 mV.

For higher photon counts, the SPAD avalanche buildup consists of two parts. In the initial part the current rise-time is much faster than exponential. The amplitude of this initial phase is roughly proportional to the initial photon number. It is expected, that this effect is caused by injecting of a number of carriers instead of just one for the case of single photon detection.

In both tested detection structures the avalanche current rise-time contains information about photon number detected in the dynamical range 1 photon to more than 3 000 photons per pulse. This is valid for optical pulses which are much shorter in comparison to the avalanche current rise-time. The avalanche pulse rise-time measurement permits to determine the photon number in involved in the detection process and to determine the detection time walk. However, for the “thick” SPAD detection structures the avalanche rise-time variations effects are combined with the additional effects of detection delay non-uniformity over an entire detection area. In contrast to it the “thin” SPAD structure K14 is suitable for photon number estimate and detection time walk compensation on the basis of avalanche current rise-time monitoring. The measured values of the rise-time difference is 600 ps for the photon number range of 1 to 10 000, it means 150 ps per one decade. This value makes possible to estimate the photon number involved in the detection on the basis of shot-by-shot output pulse rise-time measurements and the detection delay might be compensated, both in a dynamical range 1:10⁴.

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References

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