Afterpulsing in InGaAs/InP Single Photon Avalanche Photodetectors

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Abstract - **The effect of short gating pulses on afterpulsing in a single photon avalanche photodetector operating at a telecom wavelength of 1.5 μm is characterized and discussed. Comparison between short and longer overbias gate pulses shows that the number of carriers created with a 1 ns (short) gating pulse is lower than that of a 20 ns pulse, when the avalanche is dark-count generated.**

High-performance InGaAs/InP avalanche photo-diodes designed for single photon detection are optimized to generate a macroscopic electric pulse in response to a single photon. Single Photon Avalanche Photodiodes (SPADs) are biased above breakdown voltage to operate in the so-called 'Geiger Mode'. A single photon can trigger a self-sustained electron-hole generation process that gives rise to a macroscopic current pulse. A typical operation mode is to increase the bias above the breakdown for a short duration time (gating pulse) in which time the SPAD is armed for single photon detection.[1,2] Typically, the applied bias between gating pulses is kept at a steady-state waiting mode below breakdown. However, during the avalanche some carriers can be trapped in deep levels. These trapped carriers are decaying and can re-trigger an avalanche during the subsequent gating occurrences[3,4] – an effect referred to as "afterpulsing". The afterpulsing effect limits the repetition rate at which one can arm and operate the SPAD. As the repetition rate is increased, an increase in the dark counts is observed, which is caused by the afterpulsing effect. In quantum key distribution (QKD) the afterpulsing phenomenon is a limiting factor on the rate at which the encrypted traffic can be transmitted.

In this work we present characterization of dark counts caused by the afterpulsing effect for a commercially available SPAD[5]. The biasing circuit used in this work is based on [1], with a 1 ns duration biasing pulse, and varying repetition rates. The steady state bias is kept at levels that are 4V below the target over bias, with a constant 4V overbias pulse added to the steady state bias. In this system to operate the SPAD at 2V overbias, the steady-state biasing voltage is 2V below breakdown. In all measurements presented the SPAD is cooled to a steady temperature of 212K. The afterpulsing measurement is further broken down into two contributions:

1) Afterpulses generated by an avalanche caused by a preceding photon detection
2) Afterpulses generated by an avalanche caused by a preceding dark count

This measurement ability is possible with the following setup. The biasing pulses are alternated between one with no arriving photon, and the subsequent (adjacent in time) with 10% probability of a photon arriving. When this setup is operated in dark conditions where the laser pulse source is turned off, all the observed counts are dark ones. With the light source on, a photon arrival rate of 10% in every other gating pulse is used to ensure that the probability of more than one photon arriving in a given pulse is < 1%. The laser source is a pulsed 1.54 μm semiconductor laser attenuated to issue one photon every 10 biasing pulses, with a full width at half maximum of 500 ps. The photon arrival time fits well within the 1 ns gating pulse detection window. First the SPADs are gated without light, and then light is introduced for the same duration of integration time as used in the dark measurements. The dark measurement provides the intrinsic level of dark count rate (DCR), while the consequent measurement with the light on provides information regarding the additional counts introduced by the photon detection.

Fig. 1 shows the performance of the SPAD with respect to the dark count rate per biasing pulse and the afterpulsing probability. The afterpulsing probability is calculated by subtracting the DCR without illumination from the DCR measured when every other pulse is illuminated. At 20% detection efficiency this SPAD has a DCR of 2×10^{-5} per biasing pulse, which given the pulse length (1 ns) corresponds to 2×10^{4} counts/s. For 20% detection efficiency the probability that a count is caused by an afterpulse is 0.001 (0.1%) with a 500 kHz repetition rate.

Several measurements similar to that in fig. 1 were taken with rates varying between 500 kHz to 25 kHz. In fig. 2 we present the afterpulsing probability as a function of the time between biasing pulses. As can be seen, the afterpulsing probability declines the longer the biasing pulsed are separated – a phenomenon we attribute to the decay of the populated traps. As seen previously[4,5,6] no single charged-trap decay rate is evident from this measurement. A faster decay at short interval and gradual slower decay rates are evident as the interval between gating pulses is increased. For this SPAD, the measurement shows that the afterpulses are substantially reduced after 5 μs, but it takes approximately 20 μs to reach the low intrinsic afterpulse-free DCR level pertaining to that bias voltage. It is also apparent from fig. 2 that the afterpulsing probability is dependent on the overbias, but the decay rate seems independent of the overbias condition in the measured overbias range (between 1 to 3V). For a

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given acceptable afterpulsing probability, and a given detection efficiency working condition, one can determine the time between pulses – and hence the recommended repetition rate. For example, for an afterpulse probability of 0.01% at 10% detection efficiency, one can operate at a 2.2 μs between gates rate (455 kHz).

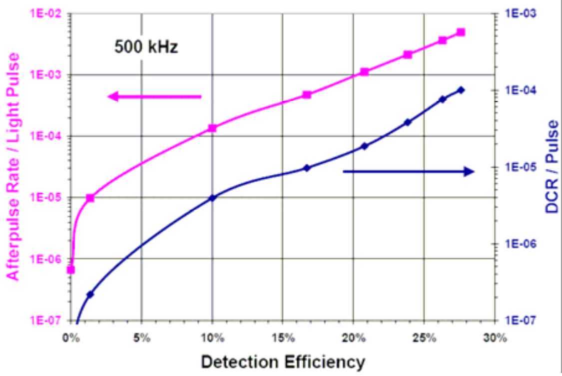

Fig. 1. Dark Count Rate per bias pulse and Afterpulsing Probability per biasing pulse as a function of the Detection Efficiency at 500 kHz repetition rate

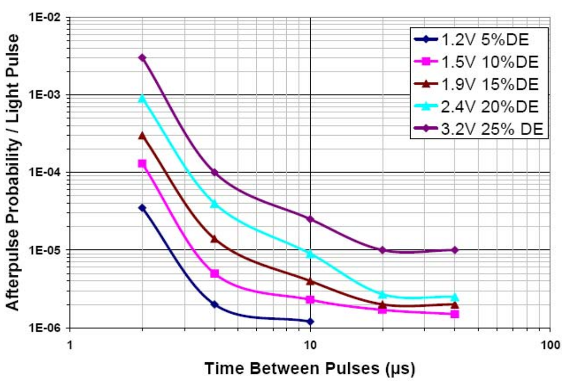

Fig. 2. Afterpulsing rate induced by a previous detection of a photon

As described above, the afterpulsing presented in fig. 2 is caused by the detection of a photon in the preceding biasing pulse. In order to isolate the contribution to the afterpulses from the dark counts alone, measurements were made without the laser source. Fig. 3 shows that the intrinsic dark count induced avalanche contributes to the afterpulsing in a different manner than the photon-illumination induced one. Any observed drop in DCR as a function of the time between gating pulses would be attributed to decrease in the afterpulsing probability.[4,6]

As seen in [6] the decay of the populated trap levels that contribute to the afterpulsing effect cannot be attributed to a single decay time constant. Different decay rates, possibly related to different mechanisms, are also observed in this work. Different decay time constants for longer hold-off times between gating pulses are assumed for the afterpulses generated by a dark-count avalanche, similar to what is observed in this work for photon-generated avalanche induced afterpulsing. Thus, the rapid time-constant decay would have occurred in a characteristic time constant shorter than 2 μs. After 2 μs, within present measurement accuracy, a slow time constant decay is observed. This longer hold-off time decay is discernable on average, as observed with the different overbias curves in fig. 3.

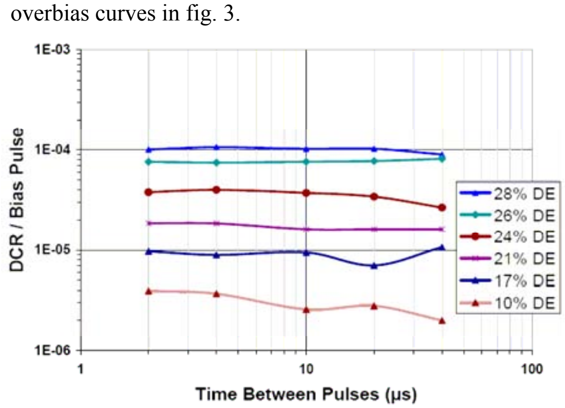

Fig. 3. Afterpulsing rate induced by an avalanche caused by a preceding dark count

The result presented in fig. 3 stands in contrast to earlier reported data taken with comparable times between pulses[5] where a 20 ns long gating pulse was used. In [5] a significant drop in DCR is observed on a time scale that is similar to that shown in fig. 2. A possible explanation is that the short gate in combination with the lower steady-state biasing voltage, generates a lower number of carriers when the avalanche is caused by a dark count. We conclude that shorter bias-gate pulses and lower voltage steady-state bias are beneficial to reduce the afterpulsing effect. Further, we conclude that an avalanche generated by photon detection – even with a short gating pulse – still generates substantial amount of carriers that are trapped in trap levels, which in turn contribute to a high probability of an afterpulse.

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