Afterpulsing Effects in 1.5 µm Single Photon Avalanche Photodetectors

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Abstract - **The effects of short (~1 ns) gating pulses and blanking on afterpulsing in an InGaAs/InP single photon detector are characterized at 1.5 µm. Afterpulse mitigation using gate pulse blanking immediately following detection events is studied, and temporal effects are discussed.**

Single photon avalanche photodiodes (SPADs) are high-performance avalanche photodiodes optimized for the detection of a single photon. SPADs are biased above their breakdown voltage to operate in the so-called 'Geiger Mode', in which 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 voltage 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 quiescent voltage below breakdown. During an avalanche event, some carriers created by the avalanche process can be trapped at defect sites in the InP avalanche region. If a trapped carrier is liberated during a subsequent gate pulse, it can trigger another avalanche, an effect referred to as "afterpulsing" [3,4]. Ultimately, afterpulsing limits the repetition rate at which one can operate the SPAD: as the repetition rate is increased, an increase in the dark counts due to afterpulsing is observed. In any application requiring single photon transmission, such as quantum key distribution (QKD), the afterpulsing phenomenon limits the rate at which single photons 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 overbias, with a constant 4V overbias pulse added to the steady state bias. For instance, 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 temperature of 212K. The afterpulsing measurement is further broken down into two contributions:

1) Afterpulses generated by an initial avalanche caused by a photon detection;
2) Afterpulses generated by an initial avalanche caused by a dark count.

These measurements were carried out using the following setup. The biasing pulses are alternated between one with no arriving photon and a subsequent pulse (adjacent in time) with a 10% probability of a photon arriving. When this setup is operated in dark conditions, for which the laser pulse source is turned off, all the observed counts are dark counts. With the light source on, a photon arrival rate of 10% in every other gating pulse ("lit" pulses) 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 generate a mean photon number of $\mu = 0.1$ per "lit" gate pulse, 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, dark measurements are made by gating the SPADs 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.

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, the SPADs studied had a typical DCR of 2×10^{-5} per bias pulse; given the pulse length of 1 ns, this DCR 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; see Fig. 1.

Several measurements with gate repetition rates varying from 25 kHz to 500 kHz were taken. In Fig. 1 we present the afterpulsing probability as a function of the time between biasing pulses, referred to as the hold-off time. As can be seen, the afterpulsing probability declines for longer separation between biasing pulses. This phenomenon is generally attributed to the exponential decay of trapped carriers from trap states in the avalanche region. 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. 1 that the afterpulsing probability is dependent on the overbias; but the decay rate seems independent of the overbias condition in the measured overbias range (from ~1V to ~3V). As seen in Fig. 1, requirements for a maximum afterpulsing probability and desired detection efficiency lead to a maximum repetition rate.

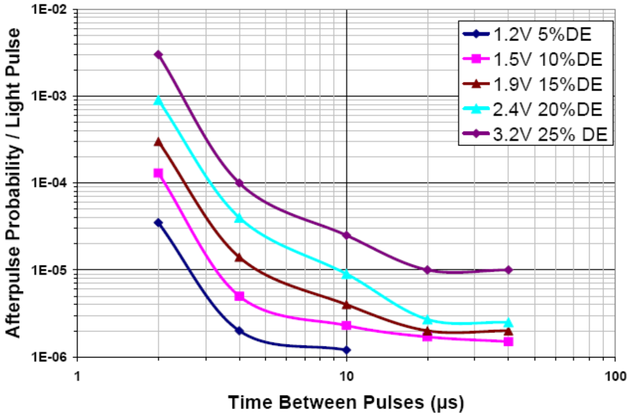

Fig. 1. Afterpulsing rate induced by previous detection of a photon.

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As described above, the afterpulsing presented in Fig. 1 is caused by the detection of a photon during a preceding biasing pulse. In order to isolate the contribution to the afterpulses from the dark counts alone, measurements were made without the laser source. Figure 2 shows that afterpulsing induced by intrinsic dark count avalanches exhibits a different behavior than the afterpulsing induced by photon detection, as seen in Fig. 1. 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] To understand this difference in behavior seen for photon-induced (Fig. 1) and dark count-induced (Fig. 2) afterpulsing, one needs to consider that in the former case, avalanches occur in at least 5% of the gates ($\mu = 0.1$ for every other gate), while in the latter case, avalanche events occur with a probability of only 1in $\sim 10^{-5}$ (i.e., the DCR). For dark count-induced afterpulsing, we can expect to resolve the contribution of afterpulsing only when the afterpulse probability is on the order of ~1 – 10%. From Fig. 1, we find that even for 25% detection efficiency and 2 µs hold-off time, the afterpulsing is only 0.3%. To see the impact of dark count-induced afterpulsing, we would need to use even shorter hold-off times.

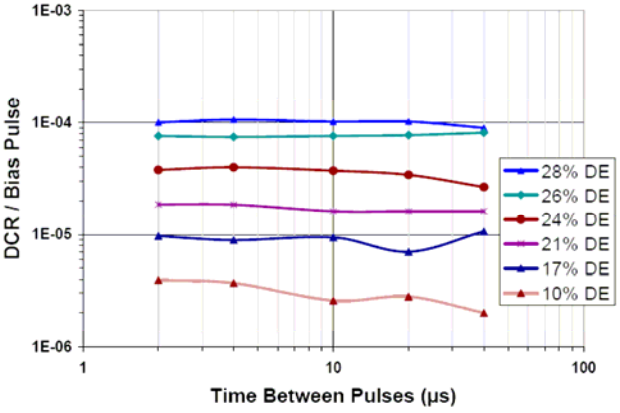

Fig. 2. Afterpulsing rate induced by an avalanche caused by a preceding dark count.

There has been considerable discussion in the photon counting literature concerning the nature of the decay of afterpulsing with increasing hold-off time.[3–7] An accurate description of this behavior, based on a physically intuitive model, should aid in determining details of the trapping phenomenon – with the goal of reducing or eliminating it – that is presumably responsible for afterpulsing effects. Since this decay has consistently been found to be more complicated than a simple exponential decrease, there has been a tendency to try to fit afterpulse versus hold-off time data with two or more exponential decays. In doing so, one makes an *a priori* assumption that more than one decay constant is involved in this process. However, recent modeling efforts that have invoked just a single decay time constant [3, 7] have been used to quite faithfully reproduce measured afterpulsing behavior and have illustrated that a single de-trapping time constant leads to afterpulsing behavior that is more complex than a simple exponential decay with hold-off time. This complexity arises due to interactions between afterpulses: a run-away process involving long strings of afterpulses initiated by just a single count is responsible for the 'super-exponential' rise in afterpulse probability with shorter hold-off times. However, the assumed underlying physical carrier de-trapping process involves just a single exponential time constant.

The result presented in Fig. 2 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. 1. It is generally believed that smaller avalanches lead to less trapped charge, resulting in less afterpulsing. Clearly, shorter gate durations would lead to less charge flowing per avalanche. A topic of further study will be to quantitatively correlate gate length and associated charge flow to specific levels of charge trapping and resulting afterpulsing.

To reduce the overall afterpulsing probability, it is advantageous to suppress gate pulses immediately following an avalanche event. This process is referred to as blanking. Our bias circuitry[1] is capable of blanking an arbitrary number of gating pulses. The highest level of afterpulsing occurs at our shortest measured interval between gating pulses (rate of 500 kHz). Thus, we characterized the blanking effect using this repetition rate, as shown in Fig. 3. For a given overbias, detection efficiency is reduced slightly due to blanking (e.g., from 20% to 19%), and this effect is taken into account. Blanking the first gate after a detection event reduces the afterpulsing probability by approximately a factor of 5, and blanking 6 gates provides additional afterpulsing suppression, by a factor of ~10 relative to no blanking.

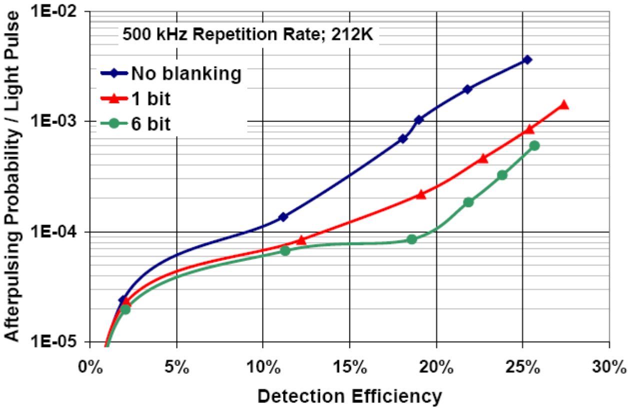

Fig. 3. Afterpulsing probability vs. detection efficient for no blanking, single-gate blanking, and 6-gate blanking; see text for discussion.

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