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OPTICAL SENSORS AND TRANSDUCERS

The Effect of High Background and Dead Time of an InGaAs/InP Single-Photon Avalanche Photodiode on the Registration of Microsecond Range Near-Infrared Luminescence

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Abstract—The effects of a high background count and a microsecond dead time interval on a gated InGaAs/InP single-photon avalanche photodiode (SPAD) during microsecond luminescence decay registration are discussed. It is shown that the background count rate of the SPAD limits its use for time-resolved and steady-spectral measurements, and that a "pile-up" effect appears in the microsecond range.

Keywords: near-infrared detector, photon counting, single-photon avalanche diode (SPAD), pile-up, counting loss

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INTRODUCTION

Single photon counting is one of the most sensitive methods to register low intensity light signals with high resolution. For many years it has been used primarily to record visible luminescence decay curves with characteristic decay times from several to hundreds of nanoseconds [1], using instruments such as the Picoquant MicroTime system. However, many samples of interest luminesce in the near infrared (NIR) region and have decay times of dozens of micro- or milliseconds. These include PbS and PbSe nanocrystals, singlet oxygen and porous silicon [2, 3]. NIR luminescence is measured by InGaAs and Ge photodiodes using an oscilloscope and InGaAs photomultiplier tubes (PMT). The most sensitive type of NIR single-photon detector is a single-photon avalanche photodiode (SPAD) based on Ge or InGaAs. These devices have a very high background count rate due to the narrow bandgap of InGaAs and a relatively long dead time. A typical InGaAs SPAD has a background count rate of about 10^4 s^{-1} and a dead time of about 10 μs. Typical data is available in the References [5]. Documentation on the ID221 SPAD, provided by ID Quantique, is also readily available. Comparable values for a typical Si SPAD are 100 s^{-1} and tens of ns, respectively.

Photon counting in time intervals up to hundreds of nanoseconds is usually carried out in time-correlated single photon counting mode (TCSPC), because TCSPC is insufficient for longer periods, those longer than 100–500 ns, and starts to require a very long accumulation time. Measurement of longer times requires the use of gated mode, in which the delay curve is divided into intervals and the total numbers of photons is counted in each interval. Another way to do this is by dividing the curve into TCSPC intervals, which are then merged. This provides a high temporal resolution. A more suitable method for measurements in the micro- and millisecond range is multiscalar counting (MSC), that theoretically allows registration of most of the photons within the measurement period simultaneously [6]. It is known that TCSPC is affected by a pile up effect [1] which becomes negligible when measuring longer time intervals using MSC. These methods of photon counting are widely used in the visible range, both for PMT and APD detectors.

The use of NIR SPAD experimentally for long luminescence decay times is subject to pile-up and requires a reconsideration of the applicability of counting methods. Additionally, the high background count significantly reduces the dynamic range, necessitating a reevaluation of the impact of counting losses. In this article, we describe how a high background count rate and a long dead time affect experimental data using a gated InGaAs/InP SPAD, supplied by Micro Photon Devices.

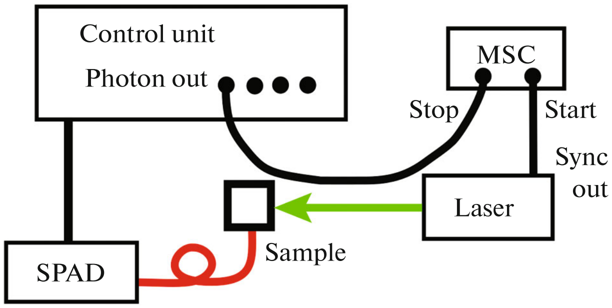

Fig. 1. Schematic diagram of devices during the experiment. SPAD—InGaAs/InP single photon avalanche photodiode (Micro Photon Devices), MSC—multiscalar photon counter DPC-230 (Becker & Hickl). Laser—pulsed laser (980 nm LDH-P-C-980 by PicoQuant, 1053/527 nm DTL-339QT by Laser-Export via pulse inverter).

EXPERIMENTS

NIR SPAD devices are of two types—gated and free-running. Synchronized gating allows a reduction in noise and an improved dynamic range, but the count is limited by gate width, with a maximum of about 500 ns, much shorter than the decay time in our case. An application note for an InGaAs/InP SPAD (MPD) [7] describes three ways in which the gated NIR detector can operate—two synchronous methods and one asynchronous. In the first method, the decay curve is divided into consecutive TCSPC/MSC intervals, no longer than the gate width, which are then merged. The second method uses MSC over the whole decay curve, the SPAD opens the gates with a frequency at least 100 times greater than the excitation laser pulse repetition rate. The laser, MSC and SPAD are synchronized with a frequency divider.

The third asynchronous method, also called "equivalent" free running mode, is the simplest, because it does not require additional equipment and remains gated. In this method, MSC is over the whole decay curve, but the SPAD is synchronized by its own frequency generator that is not connected to the laser pulse frequency generator. Photons are registered in MSC mode and the decay curve appears randomly scanned. The asynchronous mode increases the acquisition time because the SPAD continues to count photons between measured decay curves, when no signal is present. We chose this last mode because of its simplicity. A schematic diagram of the asynchronous method is shown in Fig. 1. Photon counting was carried out with a DPC-230 photon correlator, supplied by Becker and Hickl, in multiscalar mode. Default instrument settings are 168 ns gate width, 3.5 V bias, 15 μs dead time, and a background count of 10^4 s^{-1}.

Background Saturation

It is known that at levels above 10% of the maximum count rate, the efficiency becomes noticeably nonlinear due to photon overlap. This leads to saturation when measuring the intensity of spectra. With time-resolved measurements, the maximum useful count rate is 50% of the maximum count rate if pile-up effects are absent [1]. The SPAD under consideration has a dead time of 15 μs and a background count of 10^4 s^{-1}. Therefore, the background count is about 15% of the maximum count rate (67×10^3 s^{-1} for 15 μs dead time) and nonlinearity and saturation are already present when recording spectra. It is possible to increase the dynamic range of linear sensitivity by adjusting the gate width. The smaller the gate width, the lower the sensitivity and the wider the dynamic range. The maximum possible change of sensitivity is 225 times when the gate width is reduced from 450 to 2 ns. The background is decreased by the same factor and is now less than 0.2% of the maximum count rate. At gate repetition rates of the order of MHz, this method does not lead to signal distortion and has been useful for spectral calibration using a black body source.

The high background level of the detector has one more important consequence, viz. a very high sensitivity to background illumination. An increase in the level of background light reduces the time remaining for registration of the useful signal, since each registered photon leads to a long shutdown of the receiver for the dead time. This leads to an increase in the acquisition time required to register the initial signal level. A further increase in acquisition time is required to get a sufficient initial signal-to-noise ratio, even for time-resolved measurements.

We measured the influence of the background illumination on the registration of a laser pulse. The laser diode used, a PicoQuant LDH-P-C-980, produced pulses with a duration of 0.3 ns, a wavelength of 980 nm and a 2 MHz repetition rate. The laser was attenuated so that the amplitude of the pulse was equal to the background level and was sufficient for registration in one minute. The dark count rate without additional illumination was 1.2×10^4 s^{-1}. Doubling of the background had almost no effect on the signal level. A further doubling of the background count to 4.8×10^4 s^{-1} led to a reduction of the signal intensity by 400 times. The intensity fell from 2900 to 110 s^{-1} and the acquisition time increased from 1 to 16 min. Clearly, the maximum, practically achievable, count rate is much lower than 4.8×10^4 s^{-1}, since the background overwhelms the receiver, while an assumption of a uniform distribution gives a rate of 6.7×10^4 s^{-1}. Since a small increase in the background causes such a dramatic decrease in the signal intensity, it is advisable not to exceed a background level of 2×10^4 s^{-1} for time-resolved measurements. For spectral steady-state measurements, the external background illumination should be excluded and a reduction in the gate width is recommended. So, the free-running photodiode is not useful for steady-state measurements.

Distortion of the Decay Curves

It is known that the loss of a second photon detected in the same signal period as the initial photon causes an error in the detected fluorescence lifetime. This is a classic pile-up effect. The loss of the second photon within the dead time interval creates a "counting loss," a nonlinearity in the recorded intensities, and causes signal distortion. Ending the dead time causes a step change in the probability of recording a photon, leaving the lifetime unaffected [1]. These effects manifest themselves in unusual ways due to the microsecond timescale and the high background level. One example of this is when the wavelength of the excitation pulsed laser is in the spectral range of the SPAD, and these pulses reach the detector due to scattering or insufficient filtration. The initial large short pulse corresponding to laser excitation is followed by several small negative "dips" within the dead time and positive "peaks" outside the dead time (Fig. 2). Their repetition rate is equal to the gate repetition rate. This odd distribution of photons is due to the fact that a high-intensity pulse during an open gate causes a pile-up effect in the gate. In addition, it decreases the probability of detecting background pulses within the dead time. This leads to a noticeable reduction in counts for the next gate periods, which are compensated after the dead time period, forming dips and peaks. The effect is greatest when the peak arrives just after the gate opens.

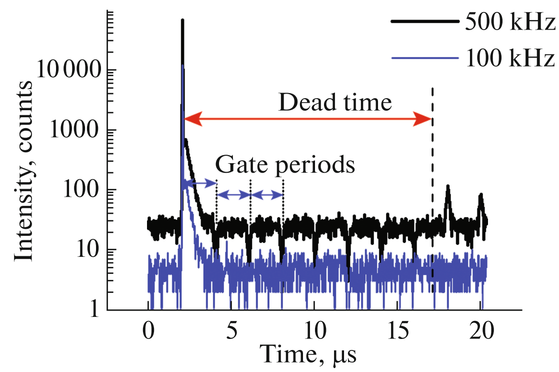

Fig. 2. Pile-up within the gate—luminescence of silicon nanowires at 1150 nm with different gate frequencies: 500 kHz (gate period is 2 μs) and 100 kHz (gate period is 10 μs).

Solving this pile-up problem is straightforward. Either reduce the intensity of the radiation (the usual way to eliminate the pile-up effect) or reduce the gate width. Reducing the gate width is less effective, because the duration of the laser pulses normally does not exceed a few ns. This is an example of where synchronization with the laser offers significant advantages, since it can allow opening of the gates with some delay after the pulse to avoid registration of the laser pulse during the initial few nanoseconds. It is possible to modify the asynchronous mode using an external gating pulse generator instead of an internal one, a delay scheme, an additional sampling pulse generator and a simple logic circuit that passes gating pulses to the "Trigger In" input of the SPAD during the active sampling pulse level only. The sampling interval should be set by the first generator, while the time shift should be determined by the delay.

A second example of decay curve distortion relates to "counting loss" and is observed when measuring intense luminescence. The measurement time is decreased due to losses in the signal during the long dead time and also because of background losses. This latter effect can even cause the decay curve to fall below the normal background level. The ability to detect photons is restored after the dead time and it is displayed on the decay curve as a sudden signal increase. If a measurement is carried out over a smaller range than the dead time interval, you may not notice the step, causing severe signal loss and lower decay times. This effect cannot be corrected. Ideally, there should be no more than one open gate registering photons during the dead time to prevent this distortion. In practice, the gate period depends on the duration and intensity of the luminescence and can be determined experimentally. In order to address this, it is necessary to decrease the gate frequency until the secondary signal increase disappears. This approach increases the measurement time in proportion to the gate period, but maintains the signal-to-noise ratio at the same level. In contrast, the customary advice to decrease the signal intensity to address this problem leads to a decrease in the signal-to-noise ratio. This effect is not noticeable when working with time intervals shorter than the dead time, so it is important to check the shape of the decay curve at longer time intervals.

To illustrate this experimentally, measurements of the luminescence of silicon nanowires [3] at 1150 nm were performed. We used excitation at 1057 nm. Various gate frequencies—200 kHz, 2 MHz, and 20 MHz were used. The signal at 20 MHz was attenuated by 20- and 200-times using filters. From Fig. 3 it is apparent that the attenuation is insufficient, leading to a decrease in the useful signal, while the background remains the same. Attenuation leads to a longer acquisition time to obtain a similar signal-to-noise ratio. In contrast, a decrease in gate frequency gives a result at 200 kHz that corresponds to a 5 μs gate period, while the dead time is 15 μs. If the lifetime is much less than the dead time, the distortion turns into an ordinary "counting loss" (Fig. 4).

It is worth discussing how these effects manifest themselves in other modes. When using a free-running diode, the regular peaks inside the dead time period will not be observed because there are not regular gates except the first large peak, which can be reduced by decreasing the signal. The main problem is pile-up within the dead time. The only way to reduce this pile-

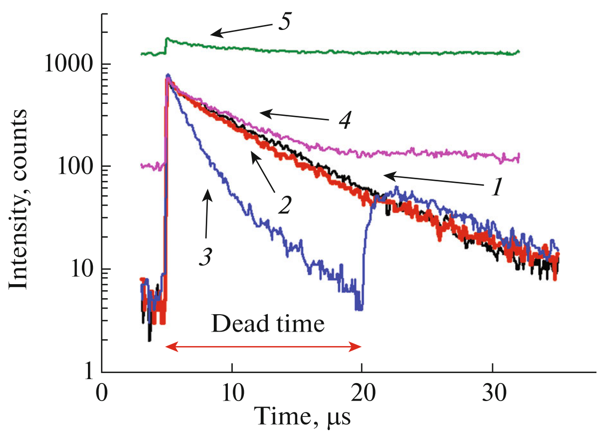

Fig. 3. Pile-up within the dead time—luminescence of silicon nanowires at 1150 nm with different gate frequencies: 200 kHz (*1*), 2 MHz (*2*), 20 MHz (*3*), and the 20 MHz signal attenuated by 20 (*4*) and 200 times (*5*). Time constants are 6.2, (6.0 + 1.0), (2.0 + 0.46), 4.5, and 4.5 µs, respectively.

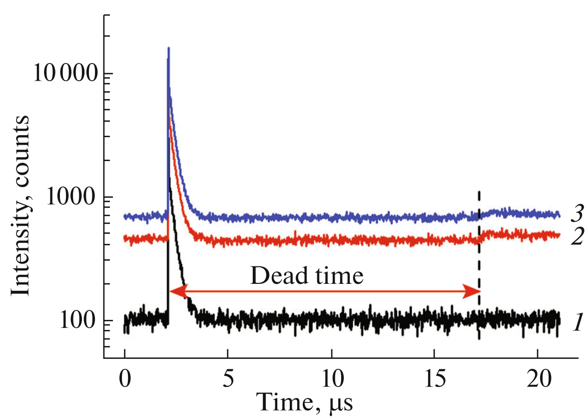

Fig. 4. Pile-up within the dead time—luminescence of silicon nanowires at 1150 nm at different gate frequencies: 500 kHz (*1*), 5 MHz (*2*), and 25 MHz (*3*). Time constants are 267, 269, and 272 ns, respectively.

up is to decrease the intensity. This is far less effective than reducing the gate width.

The method of merged intervals is associated with long measurements due to the sequential measurement of intervals, a general feature of gated counting. The method allows the influence of insufficient filtration of the laser to be mitigated since the measurement begins with a short time delay. Any pile-up effect within the dead time will be observed only within the initial interval.

Both pile-up effects will be present in the frequency dividing method as in the asynchronous method. Again, pile-up can be avoided in this method within the gate by also using a time delay.

CONCLUSION

In summary, the influence of background count rate and dead time on a NIR SPAD was discussed. It is shown that control of the level of background illumination is critical. We demonstrated how the "pile-up" effect can further distort the signal and how "counting loss" can reduce the measured lifetime.

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