IR Antibunching Measurements with id201 InGaAs Gated SPAD Detectors

Abstract. Antibunching measurements with InGaAs SPAD detectors are faced with the problems of high background count rate, afterpulsing, and the requirement to gate the SPADs. This application note describes how anti-bunching measurements can be performed by using pulsed excitation and gated detection. Possible problems of the principle are discussed and hints for the buildup of suitable experiments are given.

General Principle

Antibunching measurements based on InGaAs avalanche photodiodes (SPADs) are used to verify single-photon emission from single quantum dots in the IR at 1300 nm and beyond. However, InGaAs SPADs differ from detectors for the visible range in some important details:

- Compared with detectors for the visible range, InGaAs SPADs have extremely high dark-count rates.

- InGaAs SPADs have strong afterpulsing. When a photon was detected the diode is likely to produce a dark count in the next gate interval. This dark count produces additional afterpulses. If the total multiplication factor is larger than one instability occurs.

- InGaAs SPADs can therefore operated only in a gated mode. That means, the diode is turned on for a gate time of 2.5 to 100 ns. If a photon is detected within this time the diode delivers an output pulse. Even if no photon is detected in the gate interval the diode has to be turned off for at least 1µs until the next gate pulse is applied.

- To further reduce the amount of afterpulsing the diode is usually turned off for a period of time longer than the gate period after the detection of a photon. This ‘dead-time’ is adjusted to keep the afterpulsing intensity at an acceptable level for the particular experiment.

The traditional Hanbury-Brown-Twiss setup for anti-bunching measurements is shown in Fig. 1, left.

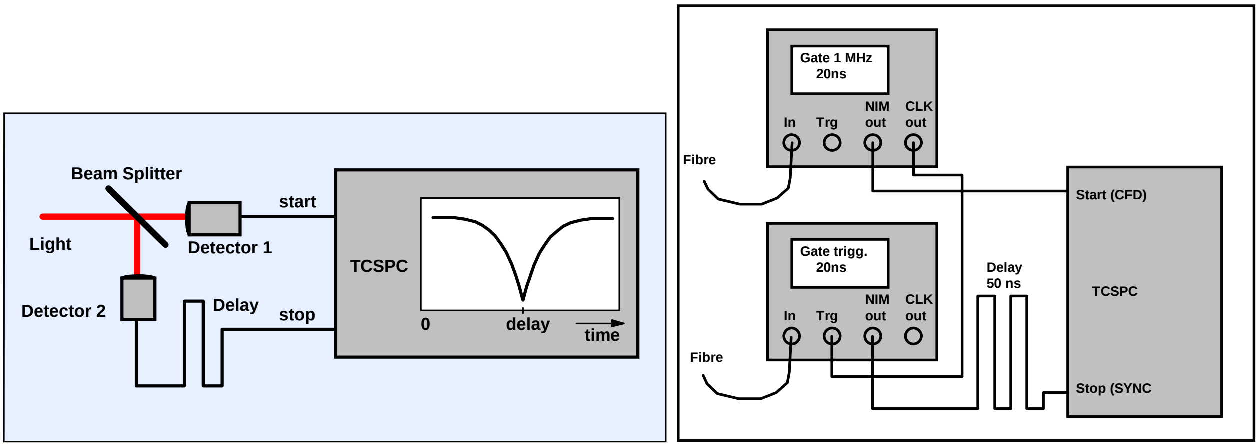


Fig. 1: Left: Traditional Hanbury-Brown Twiss experiment for antibunching measurement. Right: With id201 gated InGaAs SPADs.

In the experiment the sample is excited by a continuous laser. The light from the sample is split into two channels. Each part is detected by an individual single-photon detector, A and B. A TCSPC device measures the times between the detection events in channel A and channel B and builds up the photon distribution over these times. A single photon emitted by the sample can go only to detector A or to detector B. Therefore the distribution obtained from a single-photon emitter shows a dip at a time that corresponds to events that appear simultaneous in detector A and B. Obviously, the Hanbury-Brown-Twiss setup requires a continuously working detector. Therefore, it cannot be directly used in combination with gated InGaAs SPADs.

A possible remedy is shown in Fig. 1, right. Detector A is gated periodically ‘on’ by its internal gate generator. The gate of detector B is synchronised with that of detector A via a connection from the gate clock output of detector A to the gate trigger of detector B. A TCSPC module receiving a ‘start’ from detector A and a ‘Stop’ from detector B would detect an anti-bunching curve over a correlation time interval equal to the gate time interval.

Unfortunately, this setup works reasonably only for a correlation time interval shorter than 10 ns. For longer correlation times the high dark count rate of the SPAD results in a substantial background of random correlation events, and in a noticeable drop of the correlation curve with increasing correlation time. Moreover, there is crosstalk of the gate pulse into the detection probability, which, in turn, results in ringing in the correlation curve recorded. An example is shown in Fig. 2. Because of these problems, results obtained from the setup shown in Fig. 1, right, have not been published so far.

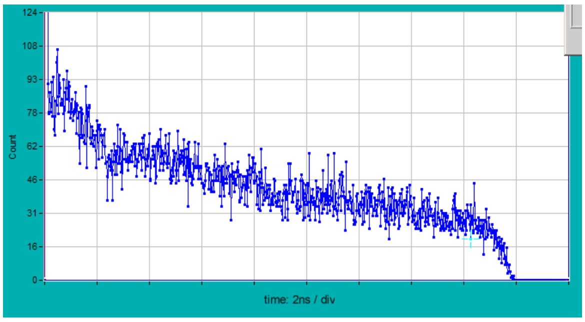


Fig. 2: Correlation background form the setup shown in Fig. 1, right. Gate width 20 ns.

Gated Antibunching Measurements with Pulsed Excitation

A solution to the problem of counting background is gated detection in combination with pulsed excitation. The setup is shown in Fig. 3.

A picosecond or femtosecond pulsed laser must be used to excite the sample. This is usually a titanium-sapphire (Ti:Sa) laser. Due to the short laser pulse a single quantum dot can only be excited one time within the duration of the laser pulse. Consequently, it can also emit only a single photon for one laser pulse, no matter how high the laser pulse energy is. To allow the id201 to gate the photons excited by the laser the repetition rate has to be reduced to about 1 MHz. A pulse picker is therefore needed in combination with the Ti:Sa laser.

An electrical reference pulse is derived from the laser via a photodiode. The reference signal triggers the gates in both id201 SPADs. The gate time should be as short as possible to keep the background count rate low. However, it should be no shorter than 50% of the excited-state lifetime of the sample. The gate delays are adjusted so that the photons emitted by the sample are inside the gate, see timing diagram in Fig. 3, right. Please note that there is some delay in the optical system. The gate delays required may therefore be in the range of several ns or even 10 ns. The exact values depend on the length of the laser light path, the length of the reference cable, the length of the detection fibres, and the internal delays of the id201.

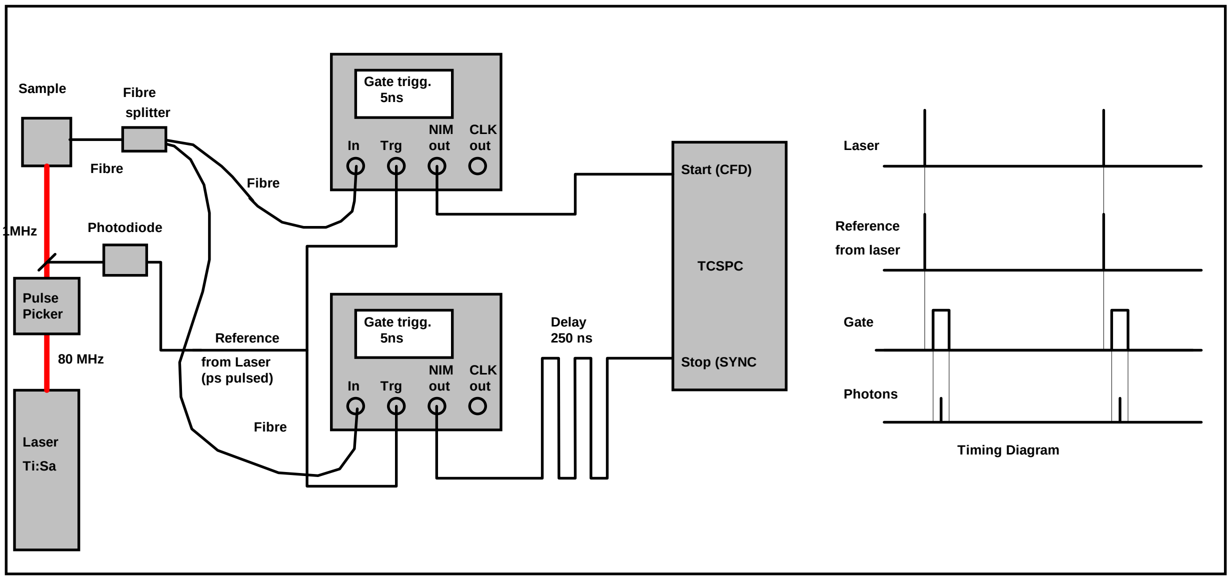
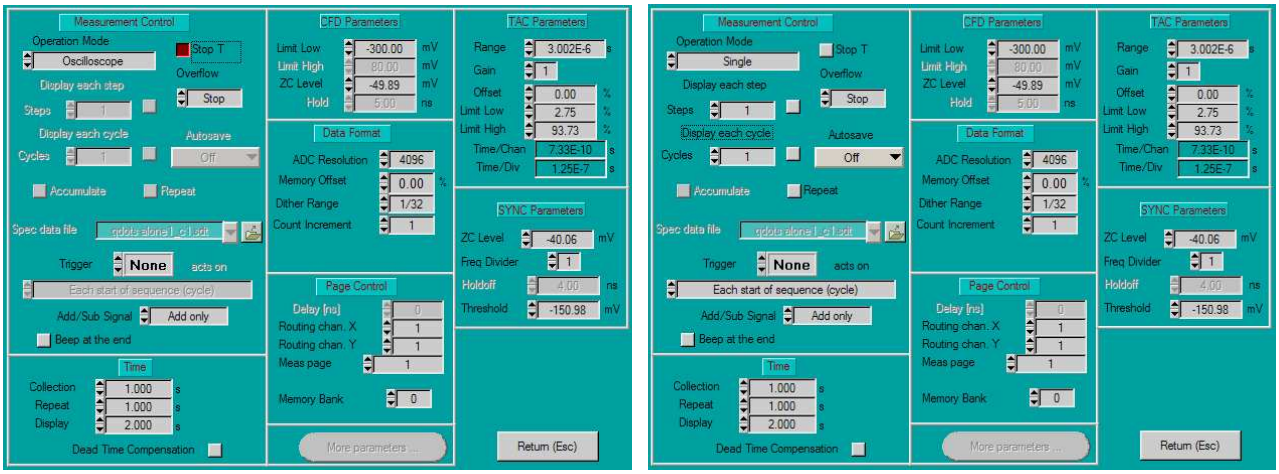


Fig. 3: Gated antibunching measurement with ps or fs laser

The output pulses of the id201 detectors are connected to the start and stop inputs of the TCSPC module [1]. The stop signal is delayed by about 250 ns in order to shift the zero-correlation peak into the recordable time interval of the TCSPC module. 250 ns correspond to about 50 m of 50-Ω cable. Any bh SPC (TCSPC) module or the bh DPC-230 photon correlator can be used. Please note that the start input of the SPC modules is marked ‘CFD’, the stop input ‘SYNC’. Please see [2] and [3] for details.

The recommended SPC system parameters for gated anti-bunching measurement with a pulsed laser of 1 MHz repetition rate are shown in Fig. 4. The setup shown left is for alignment purpose. It uses the ‘Oscilloscope Mode’ of the SPC or DPC module to display the result in intervals of 1 second.

The setup shown in Fig. 4, right, accumulates the photons until a count number of 65565 is reached in the highest channel or until the measurement is stopped by the operator.



Operation Mode Oscilloscope
☒ Stop T
Overflow Stop
Display each step
Steps 1 ☐
Display each cycle
Cycles 1 ☐
Autosave Off
☐ Accumulate ☐ Repeat
Spec data file qdots-alone1_c1.sdt
Trigger None acts on Each start of sequence (cycle)
Add/Sub Signal Add only
☐ Beep at the end
Collection 1.000 s
Repeat 1.000 s
Display 2.000 s
Dead Time Compensation ☐
Limit Low -300.00 mV
Limit High 80.00 mV
ZC Level -49.89 mV
Hold 5.00 ns
ADC Resolution 4096
Memory Offset 0.00 %
Dither Range 1/32
Count Increment 1
Delay [ns] 0
Routing chan. X 1
Routing chan. Y 1
Meas page 1
Memory Bank 0
Range 3.002E-6 s
Gain 1
Offset 0.00 %
Limit Low 2.75 %
Limit High 93.73 %
Time/Chan 7.33E-10 s
Time/Div 1.25E-7 s
ZC Level -40.06 mV
Freq Divider 1
Holdoff 4.00 ns
Threshold -150.98 mV

Operation Mode Single
☐ Stop T
Overflow Stop
Display each step
Steps 1 ☐
Display each cycle
Cycles 1 ☐
Autosave Off
☐ Accumulate ☐ Repeat
Spec data file qdots alone1_c1.sdt
Trigger None acts on Each start of sequence (cycle)
Add/Sub Signal Add only
☐ Beep at the end
Collection 1.000 s
Repeat 1.000 s
Display 2.000 s
Dead Time Compensation ☐
Limit Low -300.00 mV
Limit High 80.00 mV
ZC Level -49.89 mV
Hold 5.00 ns
ADC Resolution 4096
Memory Offset 0.00 %
Dither Range 1/32
Count Increment 1
Delay [ns] 0
Routing chan. X 1
Routing chan. Y 1
Meas page 1
Memory Bank 0
Range 3.002E-6 s
Gain 1
Offset 0.00 %
Limit Low 2.75 %
Limit High 93.73 %
Time/Chan 7.33E-10 s
Time/Div 1.25E-7 s
ZC Level -40.06 mV
Freq Divider 1
Holdoff 4.00 ns
Threshold -150.98 mV

Fig. 4: Recommended SPC system parameters for gated anti-bunching measurements. Laser pulsed at 1 MHz. Left: Oscilloscope mode for alignment of experiment. Right: ‘Single’ mode for accumulating the photons over a longer time.

Typical results are shown in Fig. 5 and Fig. 6. The curve shown in Fig. 5 has been obtained from a sample that did not show any anti-bunching effect. The result of the measurement is a number of correlation peaks. The peak on the right is the correlation of the photons of detector A versus detector B for the same excitation pulse. Please note that the SPC module uses reversed start stop; consequently the time axis is reversed. Please see [2, 3] for details. The peak in the middle and the peak on the left is the correlation between the photons of different laser pulses.

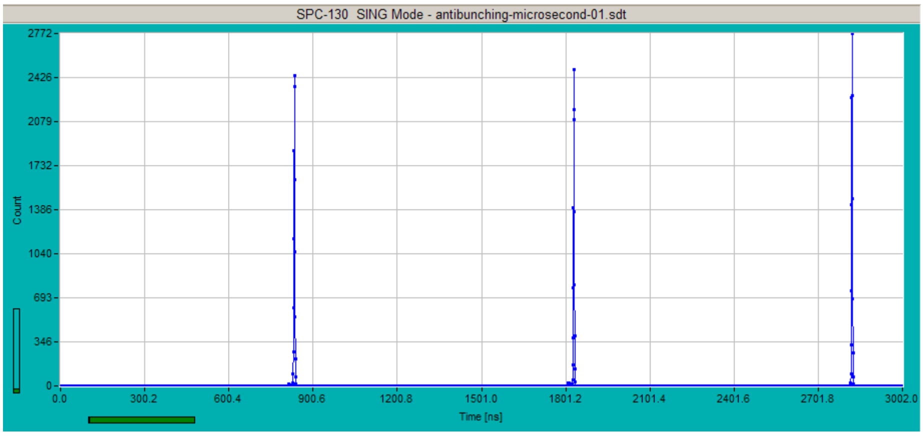


Fig. 5: Result for an uncorrelated signal from a sample without any antibunching effect

For a sample that shows antibunching the peak on the right becomes smaller, the other peaks remain the same. A result is shown in Fig. 6.

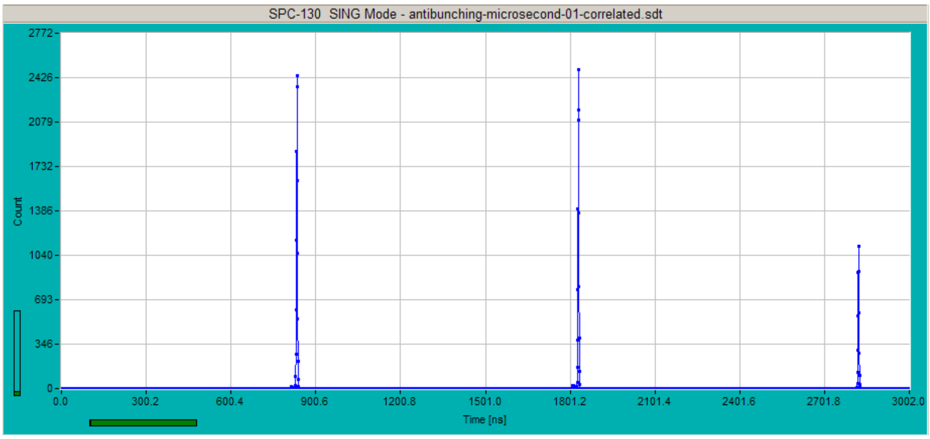
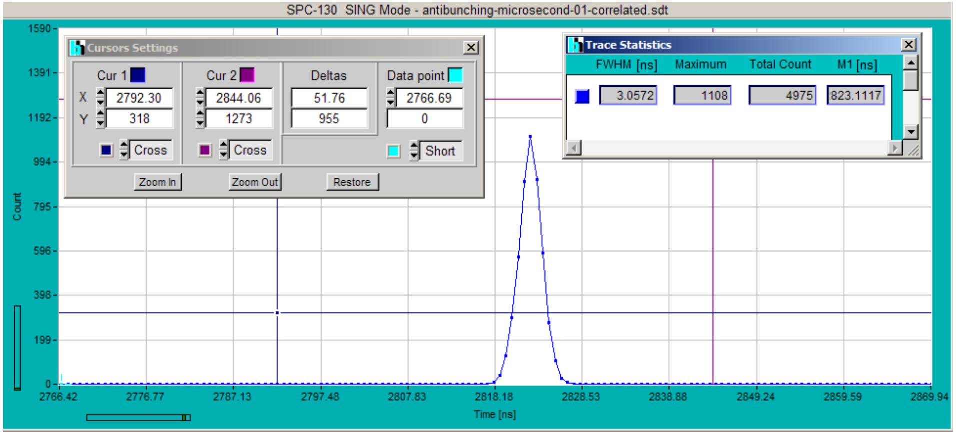


Fig. 6: Result from a sample with anti-bunching. The peak at the right becomes smaller.

Please note that the apparent peak amplitude may vary due to the distribution of the data points on the peaks. To evaluate the exact number of photons within the individual peaks, please enable the cursors and zoom into the peak of interest. Then click on the ‘Trace Statistics’ button and check the number of photons in this peak, see Fig. 7.



	Cur 1	Cur 2	Deltas	Data point
X	2792.30	2844.06	51.76	2766.69
Y	318	1273	955	0
	Cross	Cross		Short

FWHM [ns]	Maximum	Total Count	M1 [ns]
3.0572	1108	4975	823.1117

Fig. 7: Evaluating the number of photons in a correlation peak. Enable the cursors of the SPC main panel, zoom into the peak, and click on the ‘Trace Statistics’ button

It should be noted that antibunching results obtained from InGaAs SPADs are by far not ideal. Even for a perfect single-photon emitter the zero-correlation peak (on the right in Fig. 6) is not zero because it contains a number of random correlation events form background pulses. Moreover, the size of the correlation peaks obtained from an uncorrelated signal is not necessarily constant. The sizes are influenced by afterpulsing and by the dead time of the SPAD. Please note that these effects depend on the count rate in the start and stop channel. Reference measurements should therefore be performed at similar start and stop rates as the antibunching measurement.

Optical System

In should be noted that anti-bunching measurements require to excite and detect signals from single emitters, such as single molecules, nanoparticles or single quantum dots. The measurements can therefore only be done in microscope or a similar optical system. A confocal setup has to be used to confine the detection volume to a single particle. This requires perfect alignment of the optics. The laser has to be focused exactly on the particle under investigation. The light emitted by the particle is detected through the same microscope lens. It is separated from the excitation light by a dichroic beamsplitter. After passing a filter the emission light is focused on the input of an optical fibre. The input of the fibre works as an optical pinhole. The fibre input musts exactly conjugate with the particle in the laser focus. Any misalignment in x, y, or z results in loss in signal intensity and in loss of the correlation signature.

References

1. W. Becker, Advanced time-correlated single-photon counting techniques. Springer, Berlin, Heidelberg, New York, 2005
2. W. Becker, The bh TCSPC handbook. 3rd edition, Becker & Hickl GmbH (2008), available on www.becker-hickl.com
3. Becker & Hickl GmbH, DPC-230 16 Channel Photon Correlator, available on www.becker-hickl.com