Quenching Fundamentals

Module 6

SensL Technologies Ltd.
River View Business Park
Blackrock
Cork, Ireland

www.SensL.com

Contents

1 Objectives **2**

2 Quenching Fundamentals **2**

2.1 Passive Quenching 3

2.2 Active Quenching 6

2.3 Monolithic Circuits 8

3 Summary **9**

4 Acknowledgements **9**

1 Objectives

This module examines single photon detector quenching and the importance of rapid quenching. The three detrimental effects of slow quenching, namely, self-heating, afterpulsing and optical crosstalk are also outlined. The three basic quenching methods, passive, active and gated, are presented and their respective advantages outlined. After reading this module, the reader will:

- Understand quenching and the requirement for rapid quenching to alleviate self-heating, afterpulsing and optical crosstalk.
- Understand the fundamentals of passive quenching, active quenching and gated operation.

2 Quenching Fundamentals

GM-APDs (Geiger-mode avalanche photodiodes) are simply avalanche photodiodes biased above the breakdown voltage. The electric field in such a situation is so high that a charged carrier entering the depletion region causes complete electrical breakdown (also known as avalanche breakdown) of the photodiode due to impact ionisation [1]. When this avalanche breakdown occurs a self-sustaining current, in the milliamp range, flows through the GM-APD. This avalanche must be quenched by lowering the bias voltage down to or below the breakdown voltage. The bias voltage is then reset in order to detect subsequent photons.

A fast quench time is essential to ensure the magnitude of the avalanche current is kept to a minimum in order to reduce the three detrimental effects outlined below:

1. **Self-Heating:**
   Excessive avalanche current leads to the heating of the GM-APD and the

increase of the breakdown voltage. This increase in breakdown voltage leads to a reduction in photodiode bias which in turn leads to a decrease in photon detection probability resulting in substantial non-linear distortion in photon counting.

2. **Afterpulsing:**
   Afterpulsing is caused by charge carriers that become trapped in the defect centres of the silicon when an avalanche current flows through the GM-APD. Any trapped carrier may upon release trigger an avalanche which will falsely be recorded as a photon arrival. Afterpulsing can be reduced by minimising the total number of carriers crossing the junction during the avalanche.

3. **Optical Crosstalk:**
   Optical crosstalk is created by the relaxation of avalanching hot-carriers between bands in the silicon lattice [1]. When this occurs secondary photons can be emitted from the photodiode which may trigger neighbouring GM-APDs. Optical crosstalk is therefore of particular importance when there is an array of GM-APDs.

Quenching is accomplished using passive, active or gating circuitry. Section 2.1 below gives an overview of the operation of a passive quench circuit while Section 2.2 describes active quenching and gating. Section 2.3 illustrates the importance of monolithic integration for the reduction of quench time.

2.1 Passive Quenching

The simplest type of quench circuit is known as a passive quench circuit and is shown in Fig. 1(a). A passive quench circuit consists of a large resistor (100 kΩ to 2 MΩ) in series with a GM-APD. A voltage, V_{bias}, which is greater than the breakdown voltage by an amount known as the excess bias, V_{excess}, is applied to the diode. In the steady state or quiescent condition no current flows through the circuit and the entire voltage is across the GM-APD. When a carrier is created in the depletion region due to an incident photon or due to thermal generation, the diode breaks down and a large avalanche current flows through the circuit. This current results in a voltage across the load resistor and the bias voltage is then applied across both the GM-APD and the resistor.

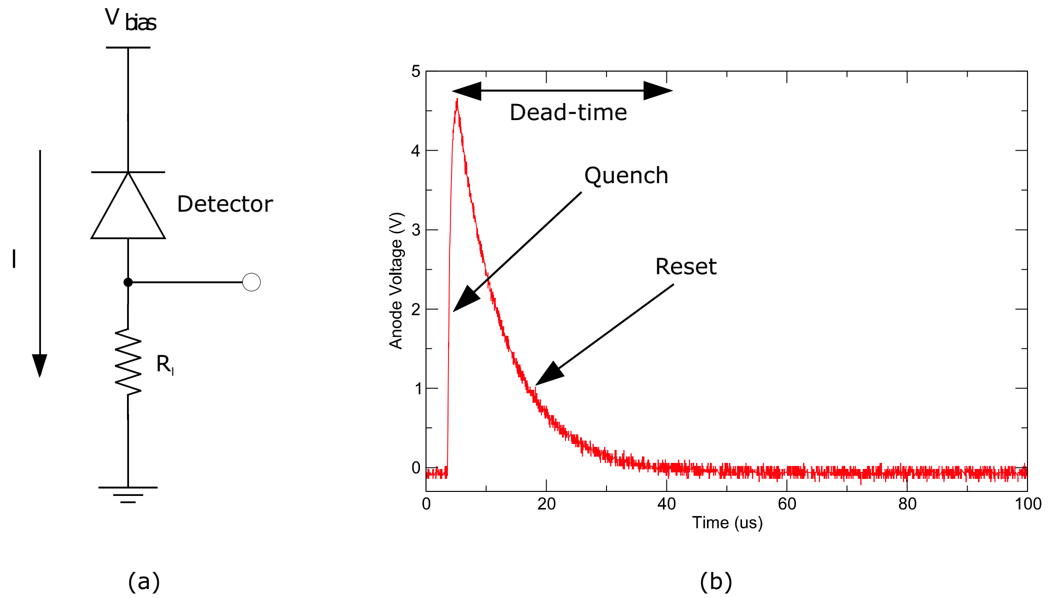

Figure 1: (a) Passive quench circuit. (b) Output from passive quench circuit.

The output from the quench circuit in Fig. 1(a) is shown in Fig. 1(b). It can be seen from Fig. 1(b) that the anode voltage or voltage across the resistor increases from 0 V to ≈ 4.6 V due to the flow of current. This is known as the quench stage, as indicated in Fig. 1(b), and the duration of the quench (≈ 0.5 μs) is known as the quench time, t_{quench}. In order to successfully quench the avalanche the voltage across the GM-APD must be lowered below the breakdown voltage. Therefore, the load resistance, R_l must be large enough so that:

$$V_{bias} - IR_l < V_{breakdown} \tag{1}$$

When the voltage across the GM-APD is lowered below the breakdown voltage, the avalanche is quenched or turned off.

After quenching the GM-APD will start to recharge through the load resistance. This recharging process is known as the reset stage and is indicated in

Fig. 1(b). Depending on the value of the load resistance the recharging or resetting will take a considerable amount of time known as the reset time, t_{reset}. The time taken from the ignition of the GM-APDs current to the subsequent return to quiescence or steady state (i.e. all the voltage again appearing across the GM-APD), is called the dead time, t_{dead}). The dead time is is given by:

$$t_{dead} = t_{quench} + t_{reset} \tag{2}$$

The quench time of the diode is governed by the time constant $R_s(C_j + C_s)$ where R_s is the diode series resistance, C_j is the diode capacitance and C_s represents the parasitic capacitance from bondpads and packaging. The reset time is governed by $R_l(C_j + C_s)$. Since the load resistor is much greater than the series resistance of the diode, which is normally just a few ohms, the load resistor dominates the dead time and must be selected to be as small as possible. Measurements made on a typical GM-APD biased 5 V above the breakdown voltage are shown if Fig. 2. The values of the load resistor were varied from 100 kΩ to 2 MΩ and the voltage across the load resistor was measured on a digital sampling oscilloscope. Clearly, as the value of R_l increases the dead time increases significantly.

The dead time of the detector affects the measured count rate since the probability of an APD detecting a photon is reduced until the voltage is completely restored across the device. The count measured from a quench circuit must be corrected to account for the dead time of the quenching circuit. The corrected count, N_{corr}, can be calculated by knowing the measured count, N_{meas}, and the dead time of the quenching circuit and substituting them into Eq. 3, which is a first order approximation to the measured count rate.

$$N_{corr} = \frac{N_{meas}}{(1 - t_{dead} \cdot N_{meas})} \tag{3}$$

Once the voltage across the load resistor begins to decay towards zero, the voltage across the diode increases. The photon detection probability increases with increasing voltage above the breakdown voltage. This increasing probability can cause the diode to reignite during quench, either due to a photon or thermally

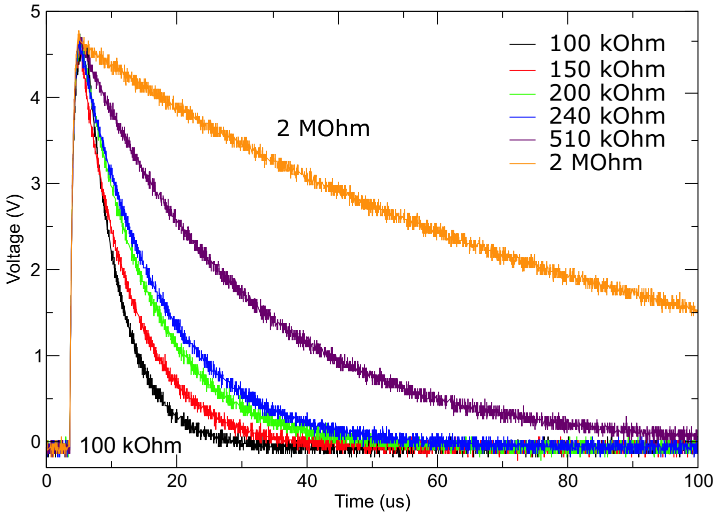

Figure 2: Voltage measured at the anode of an APD in a passive quench circuit with R_l varied from 100 kΩ to 2 MΩ.

generated carrier entering the depletion region. This reignition is shown in Fig. 3. Breakdown reignition can cause substantial problems with photon timing.

2.2 Active Quenching

The dead time during passive quench operation has been shown to depend largely on the size of the load resistor. Increased load resistance allows higher above bias operation but at the expense of the total dead time. Maximum counting frequencies of $200,000$ counts/s are possible but count rates of $50,000$ counts/s are typical with optimised passive quench circuits [2]. Furthermore, the reignition which leads to variable dead time can cause problems with photon counting statistics.

Active quenching resolves many of the problems associated with passive quenching. An active quench circuit typically combines a passive quench circuit with a fast switching circuit that lowers the bias across the diode rapidly. After quenching, the bias on the GM-APD is held below the breakdown voltage for a length of time known as the hold-off time, $t_{hold-off}$. This time duration allows trapped carriers to discharge reducing or even eliminating afterpulsing. The

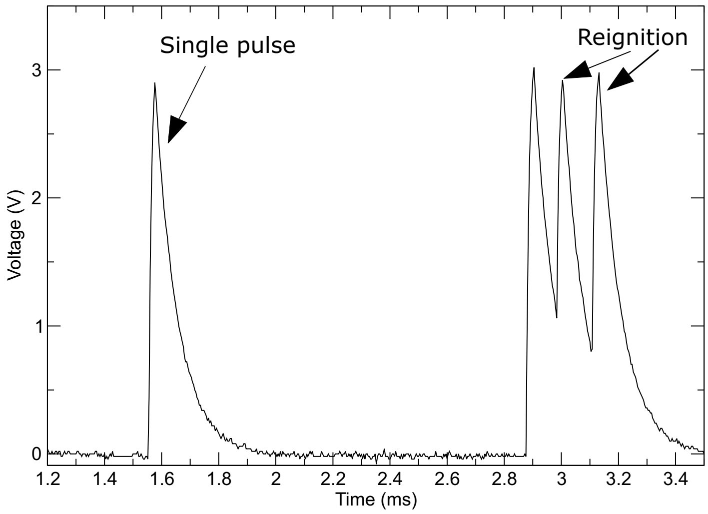

Figure 3: Illustration of reignition of GM-APD during passive quench.

circuit design usually allows for the hold-off time to be variable. This is generally achieved by varying the bias on a MOSFET or using a variable capacitor. After the hold-off time the diode is quickly recharged through a small resistance such as that of a MOSFET. This results in a very short dead time and allows very high count rates to be achieved.

An output from an active quench circuit is shown in Fig. 4 in which the passive quench, active quench, hold-off and active reset can be seen. The total dead time in an active quench circuit is therefore given by:

$$t_{dead} = t_{passive\,quench} + t_{active\,quench} + t_{hold-off} + t_{reset} \tag{4}$$

In this example the total dead time is 330 ns. The passive portion of the quench was intentionally increased to allow a better image of the breakdown cycle. The active quench can be set to occur within several nanoseconds of the breakdown pulse and dead times as low as 36 ns can be achieved [3], though in practice longer times are required to allow defects to fully depopulate to prevent afterpulsing.

Another method, known as gated operation, can be used to further increase the sensitivity of Geiger-mode detectors. When the interval between photon arrival times is known, the voltage on the APD can be varied from just below break-

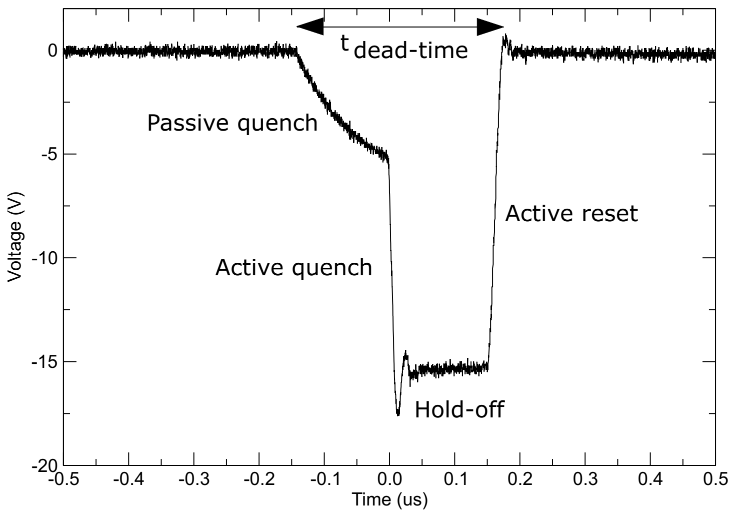

Figure 4: Active quench circuit dead time, showing passive quench, active quench, hold-off and active reset.

down to above breakdown when the photon is expected. This allows optimisation of the dead time to compensate for trapping effects and can lead to improved signal to noise ratios.

2.3 Monolithic Circuits

Ideally the GM-APD and the quench circuit should be monolithically integrated, i.e., fabricated on the same semiconductor substrate. This integration leads to reduced parasitics such as bondpad capacitance, package capacitance and wirebond inductance. These reductions result in faster quench times and decreases in diode self-heating, afterpulsing and optical crosstalk. A monolithically integrated CMOS quench circuit has been reported by Zappa *et al* [4], this circuit has a quench time of less than 8 ns and a total dead time of 30 ns. Furthermore, Rochas *et al* integrated an APD with a passive quench circuit reporting a 32 ns dead time [5] and with an active quench circuit reporting a 9 ns dead time [6].

3 Summary

This module has looked at quenching fundamentals. Passive and active quenching have been explained together with the importance of rapid quenching for the avoidance of self-heating, afterpulsing and optical crosstalk. The reader is now advised to perform Experiments 4 and 5.

4 Acknowledgements

SensL Technologies Ltd. would like to acknowledge Dr. Aoife M. Moloney of the School of Electronic and Communications Engineering in the Dublin Institute of Technology and Dr. Alan P. Morrison of the Department of Electrical and Electronic Engineering in University College Cork, for writing and coordinating the PCEdu-1 Photon Counting Fundamentals Pack.

References

[1] D. Cronin, A.M. Moloney, and A.P. Morrison. Simulated Monolithically Integrated Single Photon Counter. *IEEE High Frequency Postgraduate Colloquium 2004*, pages 9–14, September 2004.

[2] S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa. Avalanche Photodiodes and Quenching Circuits for Single–Photon Detection. *Applied Optics*, 35(12):1956–1976, April 1996.

[3] M. Ghioni, S. Cova, F. Zappa, and C. Samori. Compact Active Quenching for Fast Photon Counting with Avalanche Photodiodes. *Review Scientific Instruments*, 67(10):3440–3448, October 1996.

[4] F.Zappa, S. Tisa, A. Gulinatti, A. Gallivanoni, and S.Cova. Monolithic CMOS Detector Module for Photon Counting and Picosecond Timing. *IEEE Pro-*

ceedings of the 34th European Solid-State Device Research Conference ESSDERC 2004, pages 341–344, September 2004.

[5] A. Rochas, G. Ribordy, B. Furrer, P.A. Besse, and R.S. Popovic. First Passively-Quenched Single Photon Counting Avalanche Photodiode Element Integrated in a Conventional CMOS Process with 32 ns Dead Time. *Proceedings of the 5th International Conference on Application of Photonic Technology, ICAPT 2002*, 2002.

[6] A. Rochas, P. Besse, and R. Popovic. Actively Recharged Single Photon Counting Avalanche CMOS Photodiode with Less Than 9 ns Dead Time. *16th European Conference on Solid State Transducers*, September 2002.