Real-time dark count compensation and temperature monitoring using dual SPADs on the same chip

S. Deng and A. P. Morrison

Dual single-photon avalanche photodiodes (SPADs) integrated on the same chip enables the effective reduction of dark count rate (DCR) in the SPAD and also the real-time monitoring of the chip temperature. In the design, two identical SPADs are fabricated on the same chip, one operating normally and the other one covered by a metal layer to be kept in the dark. The two SPADs are identically biased and connected to identical active quench and reset integrated circuits. As both detectors are identical in structure, the dark count is expected to be similar for both. Experimental measurements show that the two SPADs exhibit similar DCR performance over a range of bias voltages and temperatures. By measuring the dark count rate from the covered SPAD the dark count rate from the normally operated SPAD can be accounted for directly. This can be particularly useful for SPADs where the dark count rate is high. Experiments under illumination show that the shaded SPAD is immune to illumination over a wide range of incident light power. This enables the real-time monitoring of the temperature on the sensor chip using the counting rate from the dark operated APD.

Introduction: Single photon counting techniques have been used in a wide range of low light sensing applications such as DNA sequencing, LIDAR, and medical imaging [1-3]. Traditionally photomultiplier tubes (PMTs) have been used in photon counting applications. The improvements in single photon avalanche photodiodes (SPADs) in recent years has led to this detector becoming more popular for single photon counting due to its lower-cost, higher sensitivity, lower operating voltages, smaller size and suitability for integration. When photon counting, the SPAD detects avalanche events triggered in the SPAD and produces current/voltage pulses. The avalanche events can be generated by photon absorption, thermal generation of electron-hole pairs or carriers tunnelling across the depletion region. Avalanche pulses that are not related to photon absorption are a noise source, producing a signal called the dark count. The dark count rate (DCR) should be minimised to maximise the sensitivity of the SPAD. The dark count increases with voltage and also with the temperature. The accurate monitoring of the SPAD temperature is important as a predictor of parameter variation, such as the dark count rate, breakdown voltage and afterpulsing probability. In the literature, most of the effort to reduce the dark count in SPAD is based on improving the device structure or fabrication process. In [4, 5], a balanced configuration using two APDs with only one of the APDs illuminated was proposed for SPADs in gated mode operation. It aims to cancel the common component of the output signal arising from sinusoidal gating and achieves low DCR and high PDE. The limitation remaining in the design is that the two APDs share the same output and monitoring of the individual device performance is not possible. In addition, the two APDs were not integrated on the same chip, so when one is illuminated and the other is not, the temperatures on both APDs are different and the direct monitoring of the APD temperature is not possible.

In this work, we propose a SPAD configuration that enables dark count cancellation and APD temperature monitoring. In the design, dual identical SPADs is fabricated on the same chip, with one covered by a layer of metal to be kept in the dark. Both SPADs are connected to the same active quenching and reset ICs for counting avalanche events. Both SPADs have similar performance characteristics in terms of breakdown voltage and dark count rate. The dark count statistics of the shaded SPAD can be used to estimate, in real time, the dark count of the other SPAD, thereby improving the signal to noise ratio. In addition, the temperature of the SPAD can be monitored which facilitates intelligent adjustment of the bias voltage and other parameters, such as dead-time, of the SPAD to optimise its performance.

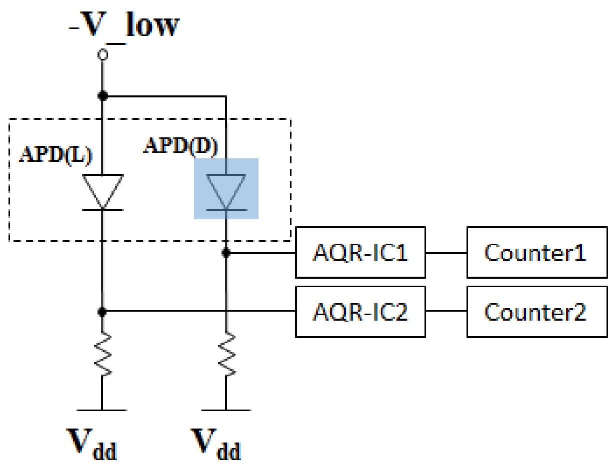

Fig. 1 *Proposed dual-APDs system.*

Design description:

Fig. 1 shows the configuration of the dual SPAD system using 20µm planar SPADs [6, 7]) fabricated on the same chip with one exposed to light (APD(L)) and the other covered by a metal layer (APD(D)). A photograph of the fabricated SPADs is given in Fig. 2a. The two SPADs are configured using the same bias voltage and series resistors. Two active quenching and reset ICs (AQR-IC), previously developed and described in [8] are shown in Fig. 2b are used to minimise afterpulsing effects and provide standard TTL pulses in response to each avalanche event at the output. The count rate measured at the output of APD(D) is used to determine the dark count at the output of APD(L) and simultaneously allows calculation of the chip temperature using the measured DCR and knowing the bias voltage.

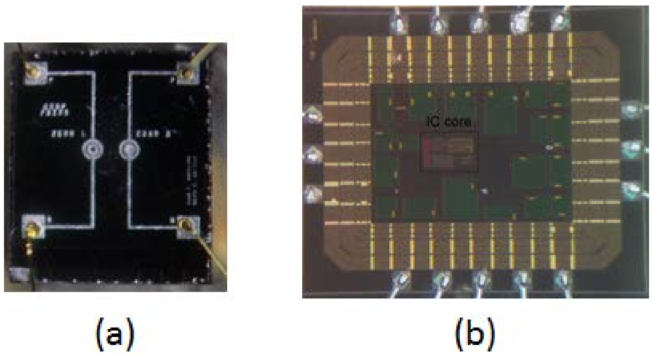

Fig. 2 *(a) Two fabricated SPADs with one shaded using a metal layer; (b) Active quench and reset IC.*

Experimental Results:

In the experiments, both SPADs are biased using a common supply. A LINKAM temperature controlled stage regulates the temperature of the SPAD chip. A 633nm laser illuminates the SPADs using an integrating sphere. The dead-time for both SPADs is set to 330 ns using the AQR-ICs.

Fig. 3 shows the measured dark count rates from both SPADs as a function of bias voltage. The temperature was fixed at 20°C and the bias voltage (Vdd+│V_low│) was adjusted from 26V to 29 V which is about 1V - 4 V above the breakdown. The measured dark count rate for both SPADs shows that the DCR as a function of bias voltage is approximately linear for both SPADs, with the shaded SPAD exhibiting slightly lower DCR over the range of bias voltage, most likely due to some stray ambient light falling on the exposed SPAD. In the measurements the DCR is compensated from 610±25 counts/s to 100±10 counts/s at 1 V excess voltage and from 1850±35 counts/s to 60±24 counts/s at 4 V excess voltage.

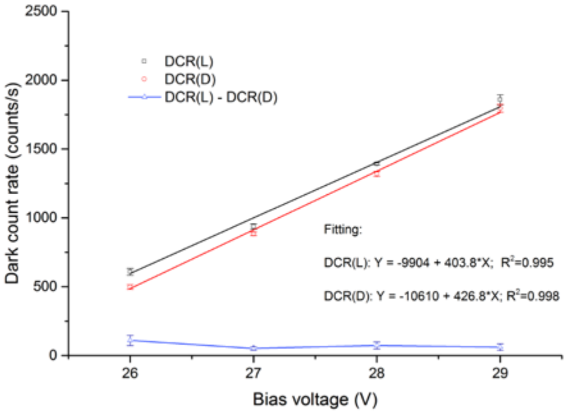

Fig. 3 *Dark count rates for both SPADs for different bias voltages, with the difference giving a fixed dark count rate offset of less than 500 counts/s over the entire bias range. Error bars represent the standard deviation.*

Fig. 4 shows the measured dark count rates from both SPADs as a function of temperature. The applied temperature is varied from 20 to 60ºC with the bias voltage fixed at 28 V. As can be seen, the two SPADs show similar DCR performance of as a function of temperature and the dark count rate of the exposed SPAD can be effectively reduced by subtracting the DCR measured using the shaded SPAD. In these measurements, the DCR is compensated from 1410±12 counts/s to 50±24 counts/s at 20ºC and from 2452±39 counts/s to 90±43 counts/s at 60ºC.

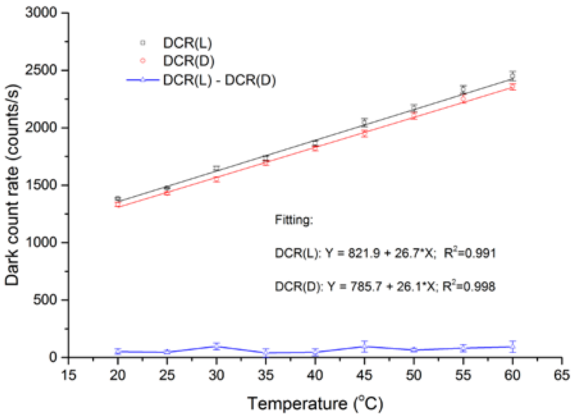

Fig. 4 *Dark count rates for both SPADs as a function of temperature at a fixed bias voltage of 28V. Error bars represent the standard deviation.*

Fig. 5 shows the measured photon count rates of the two SPADs when the chip is illuminated using a laser diode. In this experiment, the bias voltage is fixed at 28 V and the temperature at 20 ºC. From the figure, when the incident light power increases from 0 to 22nW, the counting rate on the exposed SPAD increases from 1.4 kcounts/s to 63±0.24 kcounts/s while the shaded SPAD maintains a stable count rate of 1.35 kcounts/s. Further measurements show that increasing the light power to 210 nW, the count rate on the shaded SPAD increases by less than 4% to 1.4 kcounts/s, with the exposed SPAD giving 520±5.6 kcounts/s and when the incident light power is increased to 15 µW, the count rate on the shaded SPAD increases to 1.6 kcounts/s with the exposed SPAD giving a saturated counting rate of around 3 Mcounts/s). These results show that the shaded SPAD is effectively isolated from the incident light over a wide range of power. This means that the shaded SPAD operates independent of the incident light and is only affected by variation in the bias voltage and the temperature. Thus, by measuring the dark count rate of the shaded SPAD and using knowledge of the applied bias the real-time temperature on the SPAD chip can be monitored.

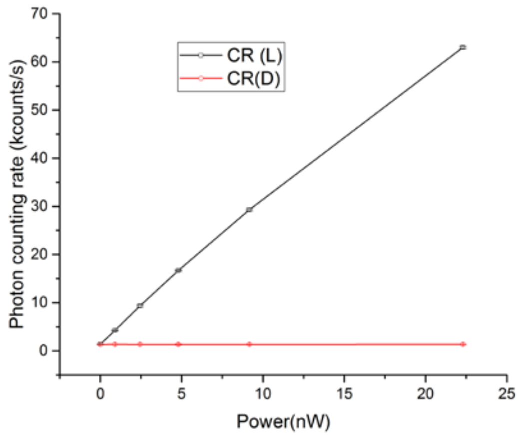

Fig. 5. *Photon counting rates in both SPADs for different laser illumination powers. Error bars represent the standard deviation.*

Conclusion:

This work demonstrates the performance of a dual SPAD-based single photon detection system that effectively separates the dark noise from the light signal while simultaneously allowing real-time monitoring of the SPAD chip temperature. In the design, the dual SPADs are fabricated on the same chip and biased at the same voltage level. One of the SPADs is exposed to light and operates normally while the other is shaded by a metal layer that eliminates light exposure. Both SPADs are connected to AQR-ICs with the same dead-time. Experimental results show that both SPADs show similar DCR performance over a range of bias voltages and temperatures. By subtracting the shaded SPAD's DCR from the signal measured using the exposed SPAD the noise is effectively separated from the useful signal. This technique can be useful for improving the performance of SPADs where the dark count rate is high. The experimental results also show that the shaded SPAD is essentially immune from illumination over three orders of magnitude from nW to µW. This enables the real-time monitoring of the SPAD temperature using the dark counting rate from the shaded SPAD.

References

1. Ken Healy, Birgitta Schiedt, and Alan P. Morrison. "Solid-state nanopore technologies for nanopore-based DNA analysis." NANOMEDICINE, Vol 2(6): 875-897, 2007.

2. Takai, Isamu, *et al*. "Single-photon avalanche diode with enhanced NIR-sensitivity for automotive LIDAR systems." Sensors, 16(4):459, 2016.

3. Veerappan, Chockalingam, Claudio Bruschini, and Edoardo Charbon. "Sensor network architecture for a fully digital and scalable SPAD based PET system." IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC), 2012.

4. Campbell, J. C., Sun, W., Lu, Z., Itzler, M. A., and Jiang, X. "Common-mode cancellation in sinusoidal gating with balanced InGaAs/InP single photon avalanche diodes." IEEE Journal of Quantum Electronics, 48(12), 1505-1511, 2012.

5. Lu, Z., Sun, W., Campbell, J. C., Jiang, X., and Itzler, M. A. "Pulsed gating with balanced InGaAs/InP single photon avalanche diodes." IEEE Journal of Quantum Electronics, 49(5), 485-490, 2013.

6. Jackson, J. C., Morrison, A. P., Phelan, D., and Mathewson, A. "A novel silicon Geiger-mode avalanche photodiode." IEEE International Electron Devices Meeting, (IEDM'02) pp. 797-800, 2002.

7. Phelan, D., Jackson, J. C., Redfern, R. M., Morrison, A. P., and Mathewson, A. "Geiger mode avalanche photodiodes for microarray systems." In Proc. SPIE, Vol. 4626, pp. 89-97, 2002.

8. Deng, S., and Morrison, A. P. "Active quench and reset integrated circuit with novel hold-off time control logic for Geiger-mode avalanche photodiodes." Optics letters, 37(18), 3876-3878, 2012.