Title	High dynamic range photo-detection module using on-chip dual avalanche photodiodes
Author(s)	Deng, Shijie; Morrison, Alan P.; Liu, Houquan; Deng, Hongcang; Chen, Ming; Yuan, Libo; Ten, Chuanxin
Publication date	2019-11-01
Original citation	Deng, S., Morrison, A. P., Liu, H., Deng, H., Chen, M., Yuan, L. and Ten, C. (2019) 'High dynamic range photo-detection module using on-chip dual avalanche photodiodes', IEEE Photonics Technology Letters, 31(24), pp. 1940-1943. doi: 10.1109/LPT.2019.2950259
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://dx.doi.org/10.1109/LPT.2019.2950259 Access to the full text of the published version may require a subscription.
Rights	**© 2019, IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.**
Item downloaded from	http://hdl.handle.net/10468/9496

High dynamic range photo-detection module using on-chip dual avalanche photodiodes

Shijie Deng, Alan P. Morrison, Houquan Liu, Hongcang Deng, Ming Chen, Libo Yuan and Chuanxin Teng

***Abstract*—In this work, a high dynamic range APD-based photo-detection module is designed and developed. In the design, on-chip dual avalanche photodiodes (APDs) are fabricated with one biased to work in linear mode and the other one biased to work in single photon mode. The APD operating in linear mode is connected to a two-stage amplifier I-V conversion circuit and the APD operating in single photon mode is connected to a custom designed active quench and reset integrated circuit. The design enables the two on-chip APDs operate in different modes simultaneously without user intervention. This simplifies the system operation and a wide range of incident light intensities can be easily detected. Experimental results show that a high dynamic range of 164.2 dB is achieved by the module.**

***Index Terms*—Avalanche photodiode; Photo-detection; Single photon counting, High dynamic range。**

I. INTRODUCTION

AVALANCHE photodiodes (APDs) have been used in a wide range of low-light, high-sensitivity sensing applications such as DNA sequencing [1], LIDAR [2], quantum key distribution [3] and medical imaging [4]. Dynamic range is an important parameter in APD based systems and is defined as the ratio between the maximum and minimum detectable power. A high dynamic range is required in optical sensing systems to prevent signal saturation when the incident light power is large or the ambient conditions change to ensure high measurement accuracy. Several approaches have been proposed to achieve high dynamic range in APDs [5-7]. In [5], F. Ceccarelli et al. describe a 152-dB dynamic range single photon avalanche diode (SPAD) based photon detector. In their design, the wide dynamic range is achieved by using a new active quenching circuit design having a maximum counting rate of 120M counts/s. However, this requires a hold-off time of a few nanoseconds which is normally not enough for the release of residual charge trapped in the APD and may lead to significant afterpulsing effects. In [6] and [7], an APD based photon detector system that allows the APD to be switched between linear mode and single photon mode (also called Geiger mode) for the dynamic range extension is described. Dynamic ranges of 100dB and 85dB are reported, respectively. Their approach only allows the APD to work in one mode at a time and its working mode must be changed by the user. Since the APD's connection schematics are very different between linear mode and single photon mode (in linear mode, the APD's anode/cathode is normally connected to a trans-impedance amplifier directly; in single photon mode, the APD's anode/cathode is normally connected in series with a resistor and also to a quenching circuit), this reduces the system's speed and makes it more complicated to use. Moreover, the high dark count that exists in their APD when working in single photon mode also lowers the overall dynamic range.

In this work, we developed a high dynamic range APD-based photo-detection module. In the design, dual APDs were fabricated on the same chip with one biased to work in linear mode and the other one is biased to work in single photon mode. The APD operating in linear mode is connected to a two-stage amplifier and the APD operating in single photon mode is connected to an active quench and reset integrated circuit (AQR-IC). This combination of the APDs and the AQR-IC, results in a dynamic range of 164.2 dB being achieved (with an 800ns dead-time in single photon mode resulting in negligible afterpulsing). Moreover, the system developed allows the dual APDs operate in the two modes simultaneously. This lowers the system operating complexity allowing for full exploitation of the dynamic range.

II. SYSTEM DESCRIPTION

Fig. 1 shows the schematic of the proposed design. Two 20 μm diameter planar APDs (APD1 and APD2) previously designed [8, 9] are fabricated on the same chip with both APDs' anodes connected to a high negative bias voltage (-Vhigh = -25V). The APDs are designed based on a shallow p-n junction and manufactured in p-type epitaxially grown bulk silicon using a 1.5 um CMOS process, which makes them suited for detection of short wavelengths of the light from 400nm to 850nm. Responsivity and photodetection probability measurements show that the APDs can obtain a peak response between 550 and 650 nm wavelength light and a 43% peak quantum

This work was supported by National Natural Science Foundation of China: 61964005, 61965006, 61805050, 61705050, 61535004; Guangxi Project: 2018AD19045, 2018JJB170037, 2018AD19033; Guangxi Key Laboratory of Automatic Detection Technology Instrument Foundation: YQ18111, YQ19106; and Guangxi Project for ability enhancement of young and middle-aged university teacher: 2019KY0211.

Shijie Deng*, Houquan Liu, Hongcang Deng, Ming Chen, Libo Yuan and Chuanxin Teng* are with School of Electronic Engineering and Automation, Guilin University of Electronic Technology, Guilin, People's Republic of China; (*correspondences: shjie.deng@guet.edu.cn; tcx19850425@guet.edu.cn).

Alan P. Morrison is with the Department of Electrical and Electronic Engineering, University College Cork, Cork, Ireland (e-mail: a.morrison@ucc.ie).

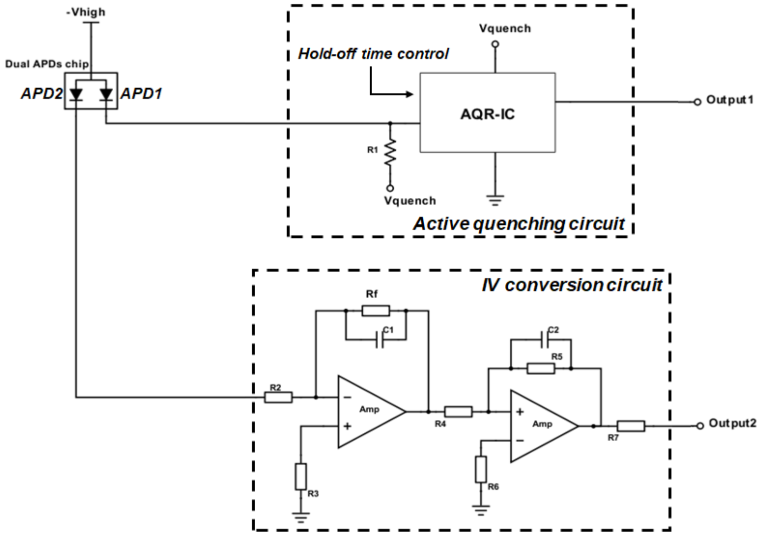
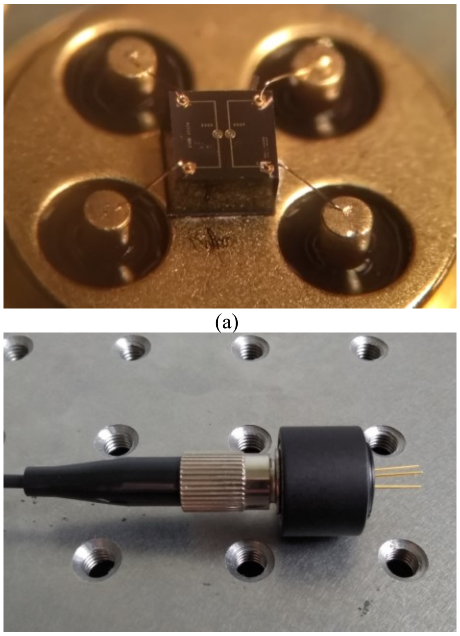


Fig.1. Schematic of the proposed design.

efficiency can be achieved at 650 nm wavelength light. The photograph of the fabricated on-chip dual APDs can be seen in Fig.2 (a) which is wire-bonded in a TO-46 package and coupled to an optical fiber adapter (see Fig.2. (b)). In the module, APD2 is reverse biased at -Vhigh and operates in Linear mode. Its cathode is connected to a two-stage amplifier for current to voltage conversion. The circuit consists of a first stage trans-impedance amplifier with a feedback resistor value of 1M and a second buffer stage with a multiplication gain of 2.


(a)

(b)

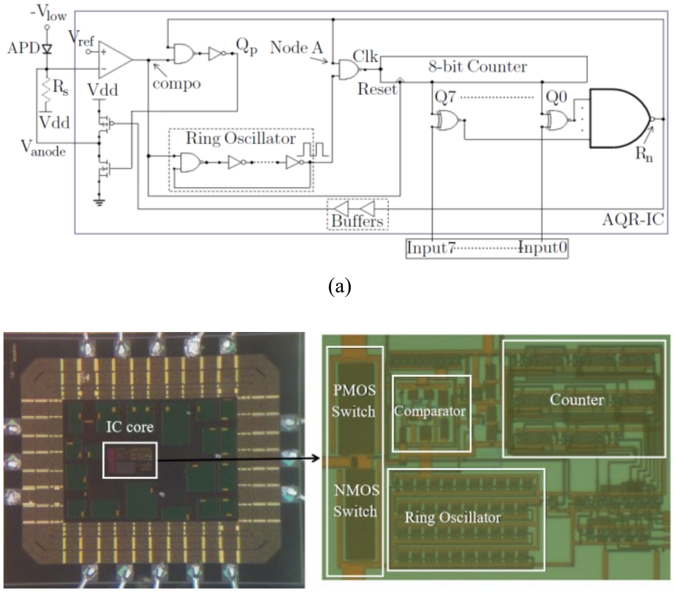
Fig.2. (a) Photograph of the fabricated on-chip dual APDs and (b) packaged APDs coupled to an optical fiber adapter.

The cathode of APD1 is connected to a resistor R1 who's the other end is connected to Vquench. This makes the reverse bias voltage of APD1 set to – (Vhigh + Vquench) and APD1 operates in single photon mode. The cathode of APD1 is also connected to an active quench and reset integrated circuit (AQR-IC) developed [10], for the maximum counting rate extension and afterpulsing effects reduction.

Fig.3 (a) shows the schematic of the AQR-IC. Its operation can be descripted as follows [10]: When there is no avalanche current, compo is set to low and the internal clock (ring-oscillator) is inactive. The counter is set to "00000000" and both the PMOS and NMOS transistors are turned off. When an avalanche event occurs in the APD, the voltage at the cathode of the APD will drop. The comparator senses the voltage change and its output "compo" goes to high. Signal at Qp goes high and the NMOS transistor will be turned on that connect the cathode of the APD to GND for quenching. Meanwhile, the ring oscillator is providing pulses to the counter which is counting upwards from "00000000" to "11111111". Each output of the counter is connected to one input of an XNOR gate. External inputs are connected to the other input of the XNOR. When the outputs of the counter equal the external inputs, Rn goes low and Qp go low. The hold-off process is stopped and the PMOS transistor is turned on to reset the APD. At this time, the ring-oscillator to the counter is blocked and the counter is stopped. Rn will remain low for resetting. When the cathode of the APD is reset, compo is low, the ring-oscillator is inactive and the counter is reset to "00000000". This makes the outputs of the counter do not match the external inputs and Rn goes high to turn off the PMOS transistor. The reset process is completed and the APD is available for the next photon detection. By varying the external inputs, the counting number can be set and the hold-off time can be altered. The AQR-IC developed allows the users to accurate set the hold-off time up to 1.6 us with a setting step of around 6.5 ns. This enables easy selection of the external input (hold-off time) for the trade-off between the maximum photon counting rate and an acceptable level of "afterpulsing". In addition, the AQR-IC is able to quench the over voltage (reverse bias voltage above the breakdown voltage) on the APD between the range of 3.3 V and 5 V (by varying its Vdd which is the Vqench in Fig. 1), which enhances the flexibility of the biasing strategy. Moreover, it can also convert

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/LPT.2019.2950259, IEEE Photonics Technology Letters

the avalanche events in the APD1 to standard transistor-transistor logic (TTL) pulses for the photon counting rate measurement. The circuit was fabricated using conventional 0.35 μm CMOS process and a photograph of the chip can be seen in Fig. 3(b).



(a)

(b)

Fig.3. (a) Schematic of the active quench and reset integrated circuit (AQR-IC) and (b) Photograph of the fabricated AQR-IC.

III. EXPERIMENTAL RESULTS

During the experiments, the -Vhigh is set to -25V which is slightly lower than the APD's break down voltage (~-26.5 V). The Vquench is set to 4 V, bringing the reverse bias voltage on APD1 to -29 V. The bias voltage decides the sensitivity and the dynamic range of the APD. For the APD1, if the Vquench is increased, the sensitivity will be improved, the noise will be increased, the detector gets saturated easier and the dynamic range will be reduced. If the Vquench is decreased, the sensitivity of APD1 will be reduced but the dynamic range will be extended. In this design, we carefully chose the Vquench so that the APD1 has a good sensitivity (this decides the lower limit of the module overall dynamic range) and in the meantime its upper limit of the dynamic range can be overlap with the lower limit of the APD2's dynamic range.

In the setup, Output1 is connected to a counter and Output2 is measured using an oscilloscope. The hold-off time in APD2 is set to around 800ns by the AQR-IC. The block diagram of the experimental setup can be seen in Fig. 4. A 650nm laser source is used with its output light guided to a filter holder (Thorlabs FOFMF/M) by a fiber and the output of the filter holder is connected to the APDs chip using another fiber. The adjustment and calibration of the intensity of the incident light directed to the APDs chip is as follows: 1. Initially, there are no attenuation filters inserted into the filter holder. The fiber from the output of the filter holder is connected to an optical power meter (Thorlabs PM100D) for initial power measurement (no attenuation); 2. The fiber from the output of the filter holder is then connected to the APDs chip through a fiber adapter; 3. A set of filters with fixed attenuation coefficient (Thorlabs NUK01) are used to be inserted into the filter holder for the output optical power adjustment. In the measurement, one or two attenuation filters are used at a same time to achieve the wanted output powers. Since the attenuation coefficient of the attenuation filters and the optical power without the attenuation are known, the output optical power from the filter holder can be calculated.

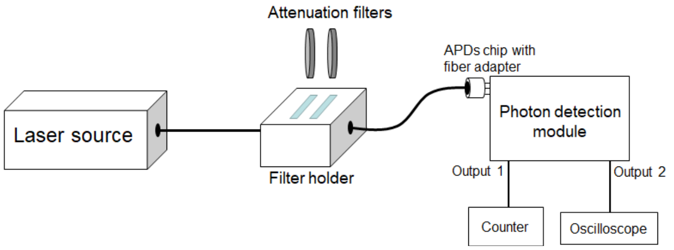


Fig.4. Block diagram of the experimental setup.

Fig. 5 shows the experimental results for APD1's (single photon mode APD) response (Output1) to different incident light intensities. Results shows that when there is no light on the APD chip, the dark counting rate from APD1 measures around 160 counts/s with a standard deviation of 23 counts/s (δ). This gives minimum detectable signal of around 229 counts/s, corresponding to an incident light intensity of 0.023nW/ mm^2. Results also show that the counting rate saturates at around 1.2Mcounts/s when the incident light intensity is greater than around 120 μW/ mm^2. In this incident light intensity range, the output of APD2(linear mode APD) based circuit is almost stable and it starts increasing when the light intensity is over around 90 μW/ mm^2.

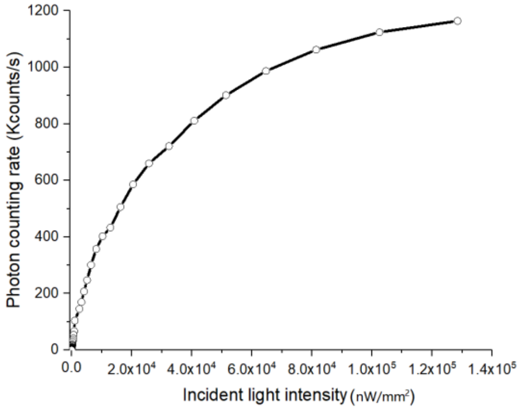


Fig.5. APD1 based circuit's responses (Output1) for different incident light intensities.

Fig. 6 shows the experimental results of APD2's (linear mode APD) response (Output2) to different incident light intensities. The results show that the minimum detectable signal (voltage differences between outputs at dark condition and when the APD is illuminated) is around 62 mV, corresponding to an incident light power of 92 μW/ mm^2. Results also show that the output signal reaches the saturation region to around 3840 mV when the incident light intensity is greater than 3.74 mW/ mm^2. All through this incident light intensity range, the photon counting rates at the output APD2 (single photon mode APD) based circuit is close to or in its saturation region.

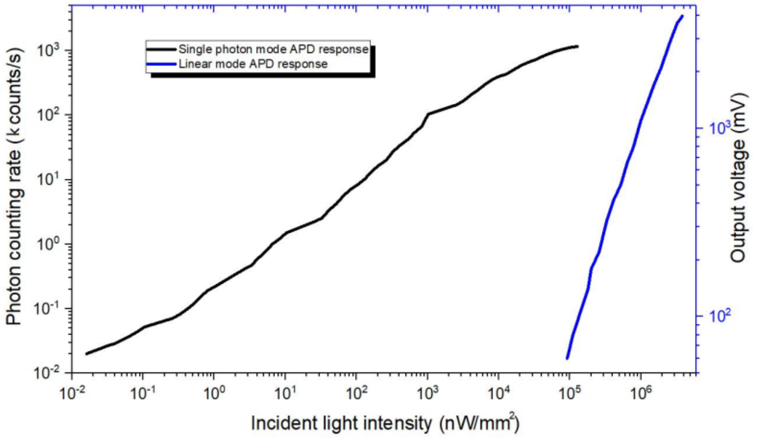


Fig.7. Results combining the dual APDs' response for various incident light intensities.

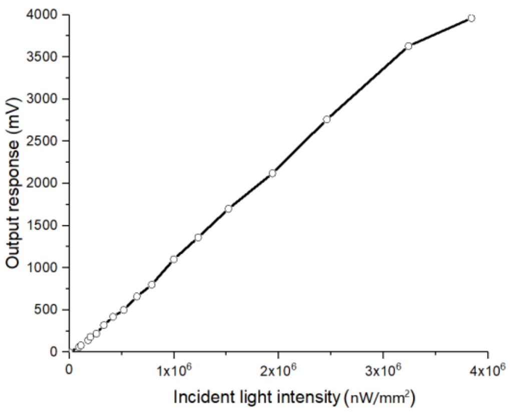


Fig.6. APD2 based circuit's responses (Output2) for different incident light intensities.

Fig. 7 shows the result of combining the outputs of the dual APD system for various incident light intensities. Results show that the dual APD detector system can provide the photoelectric conversion continuously (without any mode switching) and achieves a dynamic range of around 164.2 dB. One thing of note is that over some parts of the dynamic range, APD1's (working in single photon mode) responses is not linear with the changes in incident light intensity. If only the linear response region is taken into account, APD1 can detect an upper limit light intensity of around 1uW/ mm^2. In this case the bias voltage of APD2 needs to be increased to around 26V so that it can detect a lower limit light intensity of less than 1uW/mm2. In these circumstances, the overall dynamic range measured is reduced to around 132 dB. In addition, as there are two APDs are used, the efficiency of the whole module will be reduced (compared with using single detector) as the light power will be divided and guided to the two detectors, but the dynamic range won't be affected.

IV. CONCLUSION

In this work, a high dynamic range APD-based photo-detection module is presented. On-chip dual APDs are used in the design with one biased to work in linear mode and the other biased to work in single photon mode. The APD operating in linear mode is connected to a two-stage amplifier I-V conversion circuit and the APD operating in single photon mode is connected to a custom designed active quench and reset integrated circuit (AQR-IC). The system enables the two APDs operate in different modes simultaneously without user intervention. This simplifies the system operation and a wide range of incident light intensities can be easily detected. Experimental results show that a dynamic range of 164.2 dB is achieved by the module. If linearity is taken into account, the dynamic range achieved by the module is around 132 dB.

REFERENCES

[1] H. Ken, B. Schiedt, and A. P. Morrison, Solid-state nanopore technologies for nanopore-based DNA analysis. Nanomedicine, 2(6): 875-897, 2007.

[2] T. Isamu, I. Takai, H. Matsubara, et al. Single-photon avalanche diode with enhanced NIR-sensitivity for automotive LIDAR systems. Sensors, 16(4):459, 2016.

[3] A. Restelli, J. C. Bienfang et al. Improved Timing Resolution Single-Photon Detectors in Daytime Free-Space Quantum Key Distribution With 1.25 GHz Transmission Rate, IEEE Journal of Selected Topics in Quantum Electronics, 16(5):1084-1090, Sept.-Oct. 2010.

[4] V. Chockalingam, C. Bruschini and E. 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.

[5] F. Ceccarelli, G. Acconcia, I. Labanca, et al. 152-dB Dynamic Range With a Large-Area Custom-Technology Single-Photon Avalanche Diode. IEEE Photonics Technology Letters, 30(4):391-394, Feb. 2018.

[6] M. Mori, Y. Sakata, M. Usuda, et al. A 1280×720 single-photon-detecting image sensor with 100dB dynamic range using a sensitivity-boosting technique. IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, CA, pp. 120-121, 2016.

[7] H. Ouh and M. L. Johnston, Dual-mode, in-pixel linear and single-photon avalanche diode readout for low-light dynamic range extension in photodetector arrays. IEEE Custom Integrated Circuits Conference (CICC), San Diego, CA, pp. 1-4. 2018.

[8] J. C. Jackson, A. P. Morrison, D. Phelan, et al. A novel silicon Geiger-mode avalanche photodiode. IEEE International Electron Devices Meeting, (IEDM'02) pp. 797-800, 2002.

[9] J. C. Jackson, D. Phelan, A.P. Morrison, et al. Towards integrated single-photon-counting microarrays. Optical Engineering, 42(1):112-118, Jan. 2003.

[10] S. Deng and A.P. Morrison, "Active quench and reset integrated circuit with novel hold-off time control logic for Geiger-mode avalanche photodiodes," Optics Letters, vol. 37, no. 18 pp. 3876 - 3878, 2012.