A Review of Quenching Circuit Design Based on Geiger-Mode APD

Conference Paper · August 2018

DOI: 10.1109/ICMA.2018.8484615

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A Review of Quenching Circuit Design Based on Geiger−Mode APD

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***Abstract*-The Avalanche Photon Diode (APD) in the Geiger-mode is also called Single Photon Avalanche Diode (SPAD). It has the advantages of fast response, small volume, light weight and low power consumption and it has become the first selection of high performance single photon detection system. The quenching circuit, as the interface circuit between the SPAD detector and the Readout Interrupt Circuit (ROIC), plays a decisive role in the performance of the single photon detection system. This review first introduces the basic content of SPAD. Then, the design of the quenching circuit for the APD needed for different detection requirements is analyzed. Finally the application of APD array in laser radar technology is briefly introduced.**

Index Terms-Geiger-mode; Avalanche diode; Quenching circuit; Laser radar

I. INTRODUCTION

Single photon detection technology is a single photon-based detection technology, which can detect extremely weak light signals, and is a new detection technology developed in recent years. Photon counting is useful in many applications where single-photon sensitivity and time-of-arrival detection is critical [1].

Geiger-Mode Avalanche Photo-Diode (GM-APD) with high sensitivity and high gain have been widely used in many applications [2], and SPAD is widely used in 3D imaging, laser ranging, quantum cryptography, fluorescent decays, luminescence measurements, etc. [3]. It also can be applied to medical diagnosis, astronomical observation, defense military, spectral measurement, quantum electronics and other fields [4][5][6]. Low cost, miniature size, higher quantum efficiency and low voltage operation made the SPAD a replacement for photo multiplier tubes (PMT) in many applications today [7]. Single photon detector is the core component of 3D laser imaging system. Among the many kinds of photo-detectors currently used, there are two main types of a single photon detection capacity, Photo Multiplier Tubes (PMT) and Avalanche Photo Diode (APD) [8]. APD can work in Geiger-mode and linear mode according to its bias. When working in Geiger-mode, the avalanche gain of APD is very high, which can detect single photon, so it is also called Single Photon Avalanche Diode (SPAD). A photon absorbed in the SPAD can induce a detectable macroscopic current [9]. SPAD also has the characteristics of small response volume, fast speed, low power consumption and light quality. It has become the first choice for high-performance 3D laser imaging system [10].

The reverse bias voltage of SPAD in the Geiger-mode is higher than the avalanche voltage with extremely high current gain. Avalanche breakdown in Geiger-mode is a self-sustaining behavior. The avalanche current needs to be quenched in a timely manner, otherwise the continuous avalanche current will produce excessive power consumption, which will cause the detector to heat up and will not be able to carry out the next test. SPAD can detect and count single photon events, which can be used for laser ranging and 3D imaging in extremely low light environment [3]. Therefore, SPAD needs to cooperate with a corresponding high-speed interface circuit. The main function of the interface circuit is to quickly detect the avalanche current and extract a standard digital pulse signal for the subsequent readout circuit. Meanwhile, by reducing the anti-bias voltage of SPAD to quench the avalanche current rapidly, and reset the SPAD to the initial state, and enter a new round of pending state. Therefore, the interface circuit of SPAD is also called quenching circuit. As an interface circuit with SPAD, quenching circuit plays a decisive role in the performance of 3D imaging system. This circuit has to quench the breakdown process right after the avalanche has built-up by promptly lowering the voltage across the diode below the breakdown [11]. At present, with the development of monolithic integrated technology and hybrid integration technology and the improvement of detector production level, the scale of the laser 3D imaging system based on SPAD is gradually expanding, and the scale of the probe has expanded from the early 4×4 to 256×256 [12][13]. This review summarizes the design of the quenching circuit for the APD required for different detection requirements and summarizes the application of the Geiger-mode APD array in laser radar technology.

II. THE QUENCHING PRINCIPLE OF SAPD

When SPAD works in Geiger-mode, the avalanche breakdown caused by photons is a self-sustaining behavior. If no inhibition is taken, the avalanche will continue until the device is permanently damaged. When a photon impinges the surface of the device and is absorbed in the depletion region, an electron–hole pair is generated. Hence, due to the high electric field, additional electron–hole pairs can be generated by impact ionization thus causing the rapid rise of a macroscopic and self-sustained avalanche current [14]. In order for the device to work properly, an avalanche quenching circuit must be used to stop the avalanche process and reset the offset voltage so that the SPAD can be quickly recovered to detect the state of the photon [15]. The main function of the quenching circuit is to provide the proper bias of the sensor into the mode of the photon that can sense the photon. And the light induced current is used as the state indicator signal for the receiving of the photon. Through the I-V conversion, the stop counting signal is stopped and the normal counting function is completed. At the same time, the bias of the SPAD sensor is changed to enter the cut-off mode and wait for the next test.

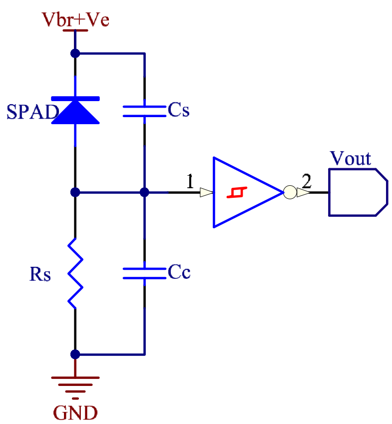

Fig. 1 Passive quenching circuit.

Passive-quenching circuits [9] [16] [17] [18] [19] [20] [21] [22] can quench the SPAD simply by developing a voltage drop on a high impedance load to lower the bias voltage of the SPAD. In order to overcome the shortcomings of long reset time and dead time of the passive quenching circuit, an active quenching method was introduced.

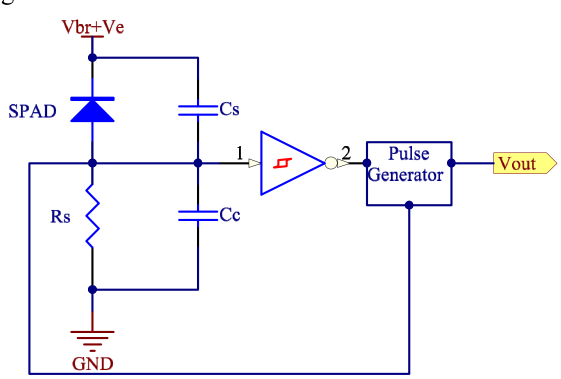

Fig. 2 Active quenching circuit.

Active quenching [23][24][25][26] is a quenching method that immediately quenches the SPAD after avalanche detection by actively reducing the voltage across the SPAD below its breakdown voltage. So the quenching time is very fast. The hold-off time is realized using an active quench and reset circuit to minimize this after-pulsing phenomenon [27].

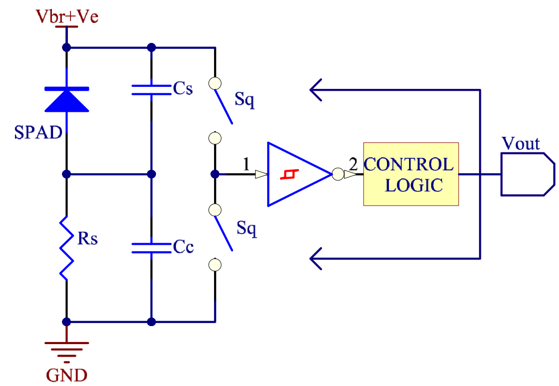

Fig. 3 Main passive mixture quenching circuit.

As shown in Fig. 3, the main passive hybrid quenching method combined with passive and active features makes full use of the advantages of the two circuits: high resistance is used as the load resistance of SPAD anode, rapid reduction and quenching structure are adopted. Once an avalanche occurs, the whole circuit is similar to the passive quenching process. When the circuit induces the avalanche signal, the active quenching is initiated and the circuit working mode is the same as the active quenching circuit. The circuit is well combined with passive and active advantages, the reduction and quenching time are short, but the structure is also more complex.

III. DESIGN OF SPAD QUENCHING CIRCUIT

A. The quenching circuit based on MOS resistance induction[28].

Induction MOS resistor M, which produces a fixed offset through a current mirror. The value of the bias current I_{QCH} is less than the quenching current I_Q of the SPAD so as to achieve the function of passive quenching. When the avalanche current is generated, the high resistance of the M1 leak can quickly sense the avalanche current and complete the passive quenching. Based on the principle of passive quenching circuit, this circuit adopts MOS high resistance instead of general resistance and reduces the area of the circuit.

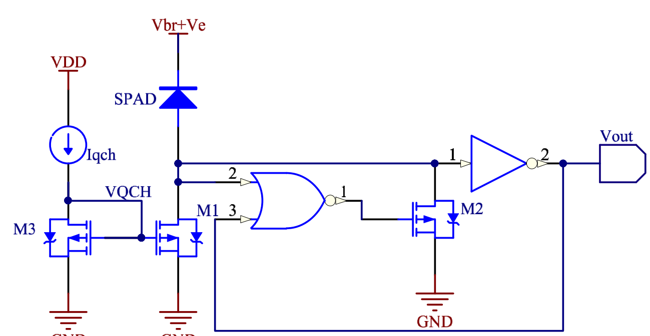

Fig. 4 Quenching circuit based on MOS resistance induction.

B. Variable load quenching circuit.

The avalanche current in the quenching circuit in Fig. 5 is induced by a voltage-controlled MOS resistor M4. Through M1, a positive feedback circuit is formed to control the gate electrode voltage of M4, so that it can work in different working areas and can change its guide resistance value. The quenching circuit is called variable load circuit [29]. Under test condition, M4 works in a linear region with small resistance, which acts as an inductive resistance. When the photon arrives, the avalanche current generates voltage at the M4 source. When the voltage reaches the opening voltage of M1, positive feedback is started, and M4 gate electrode is reduced. The M4 will first enter the saturated zone, and finally enter the cut-off zone, accelerating the passive quenching avalanche current. Therefore the whole circuit has the advantage of the main passive mixing quenching. The structure has been applied to the readout circuit of 32×32 array.

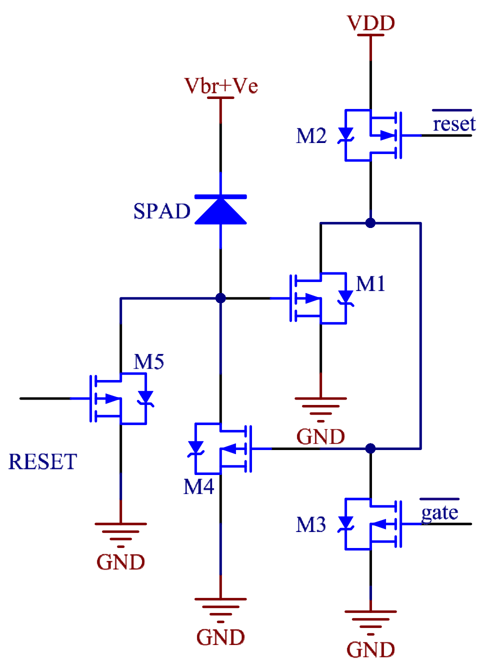

Fig. 5 Variable load quenching circuit.

C. The quenching circuit based on MOS diode.

Fig. 6 shows a quenching circuit structure based on MOS diode induced avalanche current, the PMOS diode formed by M6 functions as a sense resistor [30].The Pre and OFF signals in the figure are used to realize active reset and quenching function. After the restoration is completed, the IN point is pulled to VDD. When the photon arrives, the avalanche current is generated, the IN point voltage drops, the inverter is flipped, and the active quenching is initiated to accelerate the quenching process. The main disadvantage of this structure is that in the quenching state, M6 is always in the conduction state, and a pathway will be generated between VDD and GND to generate additional power consumption. The structure has been applied to 7×2 fluorescence detection array circuit.

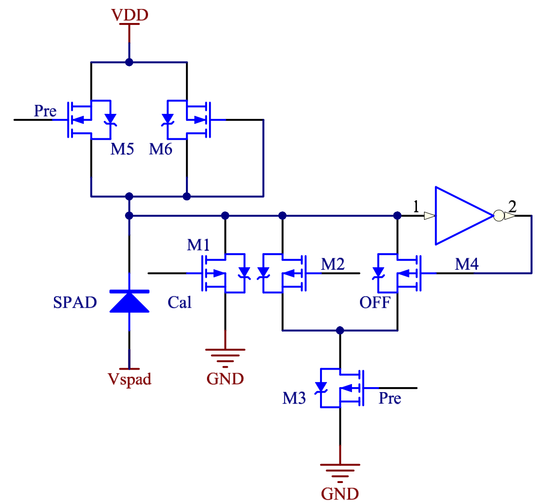

Fig. 6 Quenching circuit based on MOS diode.

D. Quenching circuit based on current mode detection [31].

The circuit adopts the current mirror to detect the avalanche current, and the circuit works directly in the current mode, which is faster than the voltage mode. In the state to be measured, the IN point is low, M2 is on, and the output is high. When the photons arrive, the avalanche current flows through the diode load M2 and the voltage controlled MOS resistor M1. Because the grid voltage of M1 is VDD at this time, its resistance is low. M2 and M3 constitute the current mirror. The OUT output decreases, the conduction resistance of M1 increases and the IN point voltage increases. In the detection process, the positive feedback formed by M1, M2, and M3 plays a role of active quenching. The variable load M1 plays a role of passive quenching. The entire circuit also has the characteristics of active and passive quenching circuits. The circuit has been successfully applied to the 8×8 detector array.

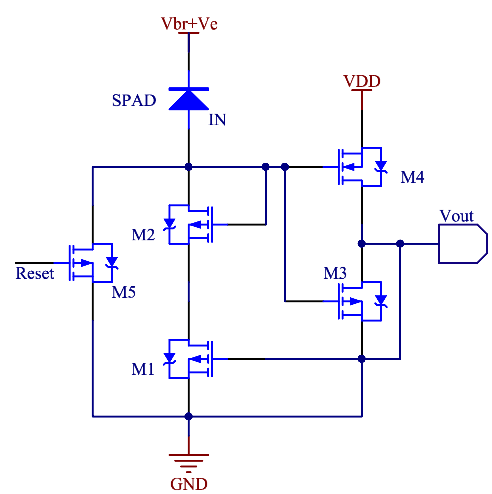

Fig. 7 Quenching circuit based on current mode detection.

E. The structure of quenching circuit based on parasitic *capacitance induction.*

As shown in Fig. 8, the quenching circuit structure proposed by Vilella et al. based on parasitic capacitance sensing [32]. The circuit uses the parasitic capacitance of the IN point to sense the avalanche current. After the avalanche current is generated, the SPAD anode parasitic capacitor is charged, which makes the anode voltage increase, and the reverse bias voltage of SPAD is reduced to below the avalanche breakdown voltage, and the passive quenching is completed. RST and INH implement active reset and gated functions, respectively.

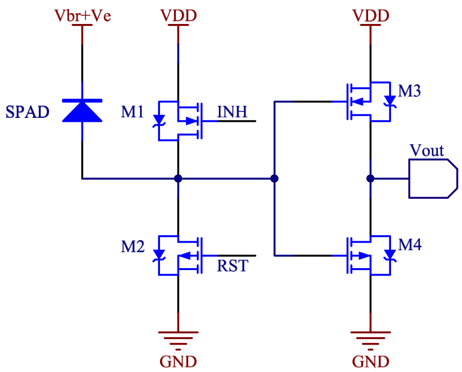

Fig. 8 CQC structure schematic diagram proposed by Vilella et al.

F. *The structural schematic diagram of CQC adopted by Lincoln laboratory.*

Fig. 9 shows the schematic diagram of the quenching circuit proposed by the MIT Lincoln laboratory [33]. The quenching circuit uses capacitive induction avalanche current, combined with active quenching, to further increase the quenching speed. The structure has been successfully applied to the 256×64 readout circuit array.

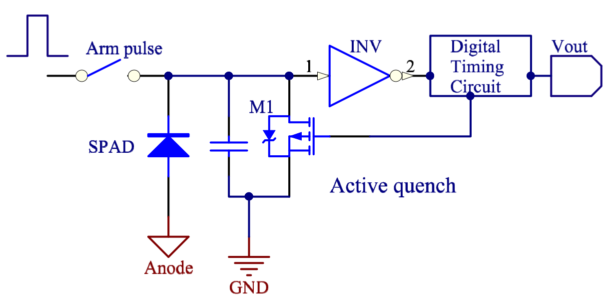

Fig. 9 Schematic diagram of CQC structure adopted by Lincoln laboratory.

G. *Design optimization based on capacitive induction quenching circuit [34].*

The quenching circuit in large array application needs to meet the basic requirements of small area and low power consumption. For a quench circuit applied to a large array, the passive quenching method has a slow response speed, and the use of a large resistor occupies the layout area, which is not conducive to the expansion of the array size, so it is generally required to adopt an active quenching method to increase the quenching speed.

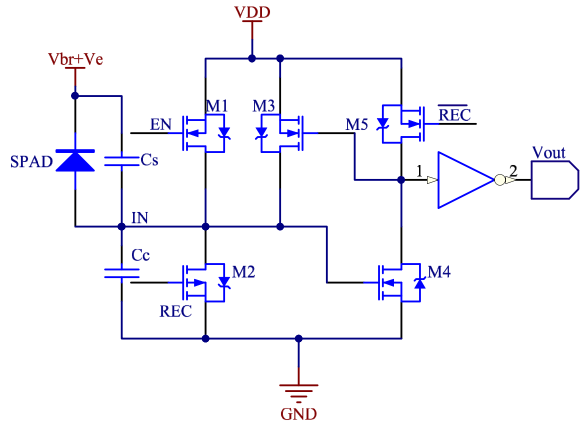

Fig. 10 Structure of capacitor quenching circuit.

The structure of the capacitor quenching circuit is shown in the Fig. 10. Cs is the junction capacitance of the APD, and Cc is the sum of the parasitic capacitance of the IN point to the ground. In the Fig. 10, M1 is a gate control tube to realize the gate control function. M2 is the reset tube, the reset circuit is in the state of being tested, and M3 is the active quenching tube, accelerating the quenching process of the circuit. The detection comparator is implemented with a single-tube M4, minimizing area and power consumption. IN the end, the output inverter improves the drive capability of the output, on the other hand, the signal is reversed to obtain the same increase along the signal as the IN point voltage polarity, which can be used by subsequent D triggers.

H. *Compact Active Quenching Circuit [35].*

The active quenching circuit must perform the following functions

- The start of an induced avalanche current.
- Generates output pulses synchronized with avalanches.
- The bias voltage of the diode is reduced rapidly.
- The initial bias voltage is restored after a controlled release time (active reset) so that the diode is ready to detect subsequent photons.

In order to reduce the possibility of detecting the photon during the recovery diode voltage, the reset conversion must be as fast as possible. The simplified schematic diagram of the circuit is shown in Fig. 11.

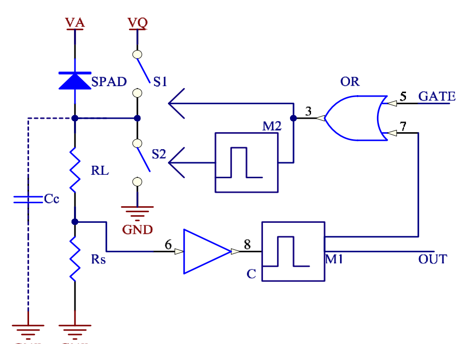

Fig. 11 Simplified block diagram of compact active quenching circuit: C is a fast comparator, M1 and M2 are fast veneers.

In standby mode, switch S1 and S2 open. When a photon is detected, a fairly high passive load provides a fast passive quenching or at least quasi-quenching by lowering the avalanche current to a very low value. After a short delay (usually 10ns), the active loop is confirmed or extinguished by the comparator C, monostable M1 and extinguishing switch S1. Extinguishing pulse duration (retention-time) is precisely controlled by single-state M1. Once the quenching pulse terminates, the bias voltage on both ends of the photo-detector is quickly restored to V_A by switch S2. The duration of the reset pulse is determined by the single stable M2, which is triggered by the negative jump of M1.The reset time must be long enough to ensure full recovery of the SPAD voltage, otherwise the comparator will be retriggered, causing oscillations.

IV. APPLICATIN OF GEIGER-MODE APD IN LIDAR

Geiger-Mode Avalanche Photo-Diode (GM-APD), which has ultrahigh sensitivity and high-resolution timing, is widely used with the technique of time-correlated single-photon counting (TCSPC) in Lidar systems to detect the weak echo-pulse in low-light-level environments [36]. Geiger-Mode Avalanche Photo-Diode (GM-APD) offers 3D imaging Lidar much better capability in terms of detection sensitivity [36]. In 2002, Lincoln laboratories developed three generation of experimental systems including GEN-I (Brassbord), GEN-II, GEN-III [37], Jigasw Ladar Sensor and ALIRT test system were developed in 2003 and 2011 respectively. In the GEN-I system, the 4×4 APD array is packaged as a stand-alone device integrated onto a printed circuit board. Each APD unit corresponds to a pulse amplification circuit, which the amplified pulse signals are transmitted through coaxial cable to the timing module. In the GEN-II system, the 4×4 APD array integrates CMOS chips with 16 timing circuits. The GEN-III system uses sensors that integrate the 32×32 APD array and 32×32 CMOS timing circuit array completely, there are more phase elements and higher integration.

In 2003, the team led by Richard M. Marino developed the Jigsaw Ladar Sensor system, which is characterized by the ability to identify objects that are hidden behind leaves and camouflage nets **Error! Reference source not found.**.

In 2011, the Lincoln laboratory completed the development of the Airborne Ladar Imaging Research Testbed system with the support of the U.S. Air Force. Lincoln Laboratory has developed 32×32 pixel Ladar focal planes comprising silicon Geiger-Mode Avalanche Photo-Diodes and high-speed all-digital CMOS timing circuitry in each pixel [39]. Fig. 12 shows the schematic diagram of the ALIRT system, and the ALIRT uses a 32×128 GM-APD focal plane timing array to achieve wide, fast, three-dimensional imaging with an angular encoder [40]. The Lincoln laboratory also designed the GM-APD data readout subsystem for the ALIRT system with a reading rate of 160MB/S. In order to accurately place the generated 3D distance images in the world coordinate system, ALIRT has installed GPS and IMU to determine the position and direction of the aircraft.

Antoine Coyac1 et al. present a 3D laser imaging end-to-end simulator using a focal plane array with Geiger-Mode detection, named LANGDOC. This work aims to highlight the interest and capability of this new generation of photo-diodes arrays, especially for airborne mapping and surveillance of high risk areas [41].

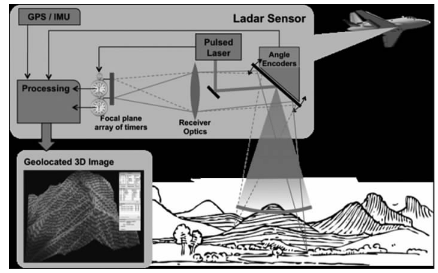

Fig. 12 Principle block diagram of ALIRT system.

V. SUMMARY

Single Photon Avalanche Diode (SPAD) has gained a prominent role in the measurement of optical signals, driven by the need for ultimate sensitivity in various scientific and industrial applications [42]. At present, most of the domestic methods for quenching SPAD and extracting avalanche signals are still in the stage of theoretical [43] or discrete devices [40]. Although the Reference [37] proposed an integrated quenching method, because of the passive quenching method, a larger resistance ($100\,\mathrm{k}\Omega$) is used, which is not suitable for the array type SPAD. The array SPAD needs the corresponding compact small area integrated quenching circuit. As the interface circuit of SPAD detector and readout circuit, the quenching circuit plays a decisive role in the performance of the imaging system. According to different design requirements, the corresponding quenching circuit has theoretical and practical value in practical application. Finally, the application of the Geiger-mode APD in Lidar is summarized, which lays a foundation for our next research.

ACKNOWLEDGMENT

This work was supported by the Basic National Defense Research Project (JCKY-2016411C006).

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