Quenching Technique Design for Optimal Performance of InGaAs/InAlAs Single-Photon Avalanche Diodes

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Abstract

Single Photon Avalanche Diodes (SPADs) made from III-V semiconductors exhibit superior detection efficiency in the infrared range compared to silicon-based SPADs, which is suitable for applications such as Quantum Key Distribution (QKD) and photonic chips. However, III-V semiconductors often contain defects that trap photons, leading to afterpulsing effects. This increases the dark count rate (DCR) and reduces detection efficiency. Previous research shows that adopting Passive Quenching with Active Reset (PQAR) circuits and operating in gated mode can help mitigate this issue. This independent study aims to design PQAR that is suitable for SPAD produced by our lab, which optimizes the performance of the device.

Introduction

SPAD, a PIN diode with a SAGCM structure, operates in Geiger mode, amplifying photocurrent. The intrinsic layer comprises an absorption layer and a multiplication layer, separated by a grading layer. The absorption layer absorbs photons, generating electron-hole pairs, while the multiplication layer amplifies these pairs. Our lab further divides the multiplication layer into three layers with charge layers inserted between them to ensure more uniform electric field distribution.

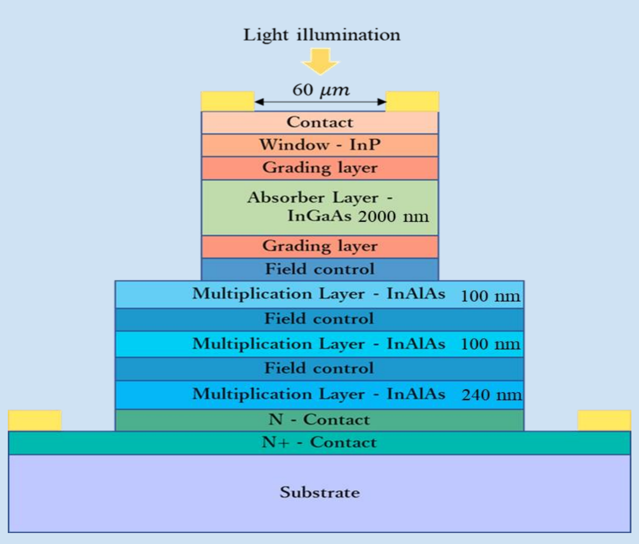

Fig. 1 Triple M-layer Mesa SPAD

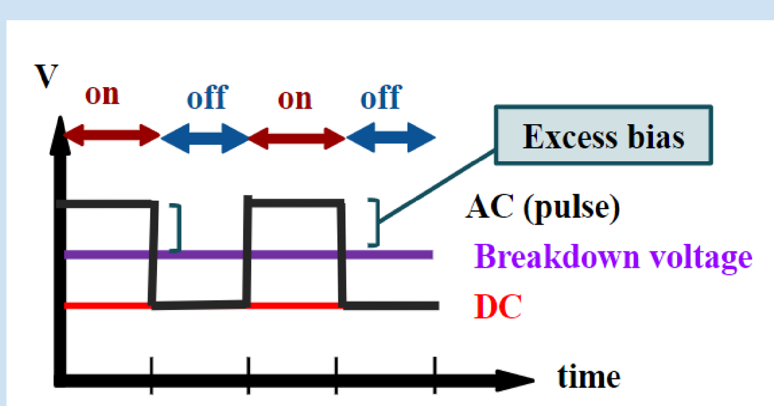

Fig.2 Gated mode operation

A quenching circuit is essential to control breakdown and recovery. The simplest quenching circuit is the Passive Quenching Circuit (PQC), as demonstrated in Figure 3. Our designed PQAR builds upon the PQC structure, incorporating an additional transistor to achieve active reset and reduce afterpulsing.

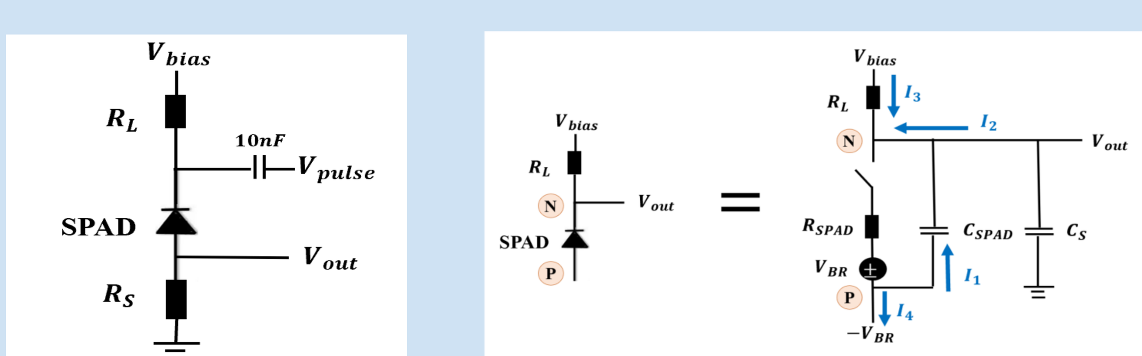

Fig. 3 (a) Gated mode PQC (b) Equivalent circuit of SPAD

Temperature significantly impacts SPAD performance. Higher temperatures decrease thermal stability and increase tunneling, leading to a higher dark count rate (DCR).

Methodology

The designed PQAR circuit, shown in Figure 4, was simulated in LTSPICE and designed in Altium Designer for PCB fabrication. For practical implementation, the circuit was divided into three parts: Part A provides the gated pulse input, Part B houses the SPAD within a cryostat, and Part C, the primary design, incorporates a JFET to optimize performance.

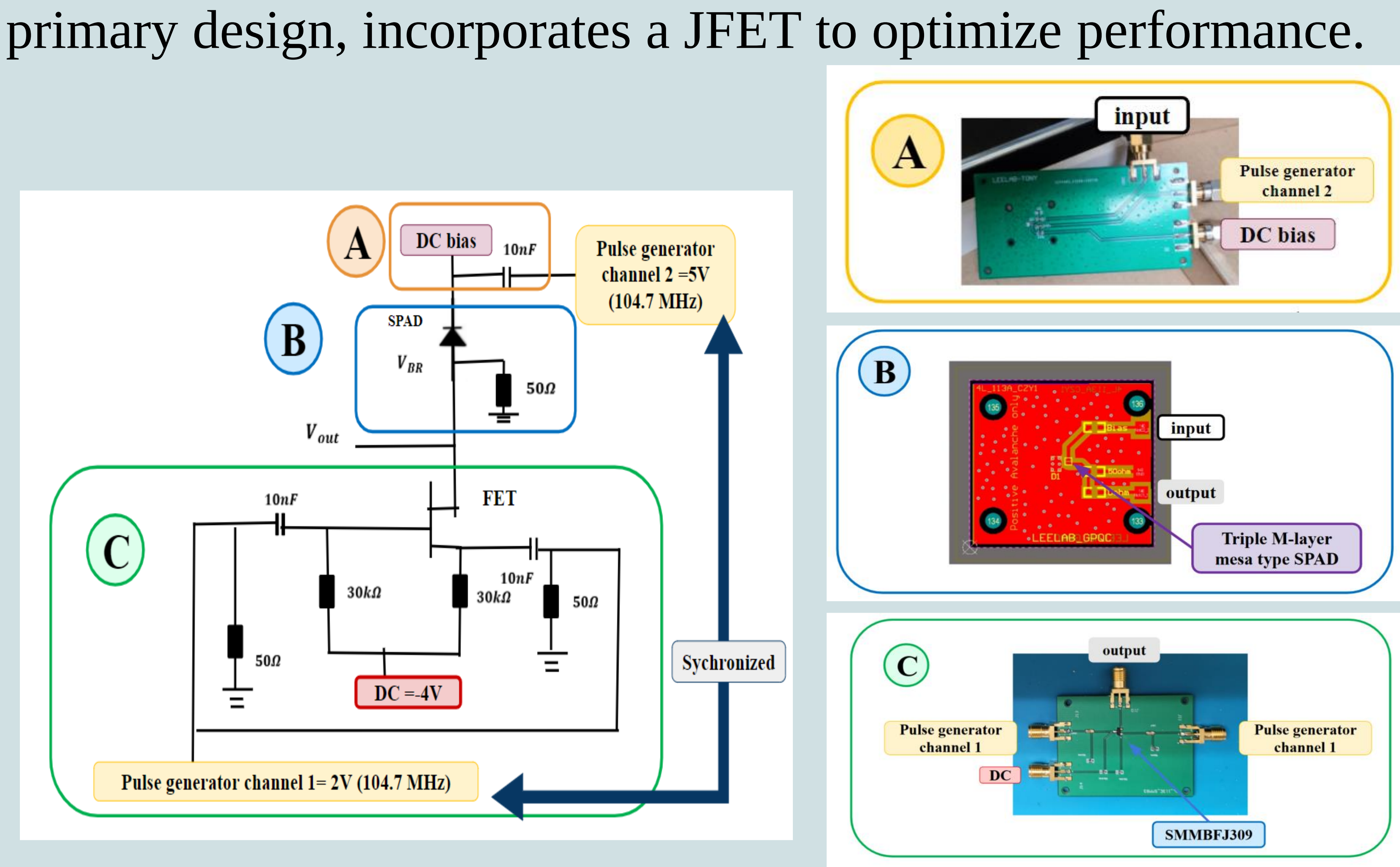

Fig. 4 Designed PQAR circuit

The PQAR circuit combines SPAD avalanche signals with periodic signals from a JFET to shape waveforms. The circuit also includes an active reset mechanism triggered by a counter. To minimize parasitic signals, the output signal is delayed through transmission lines of different lengths and filtered by an SD circuit, as shown in Figure 5.

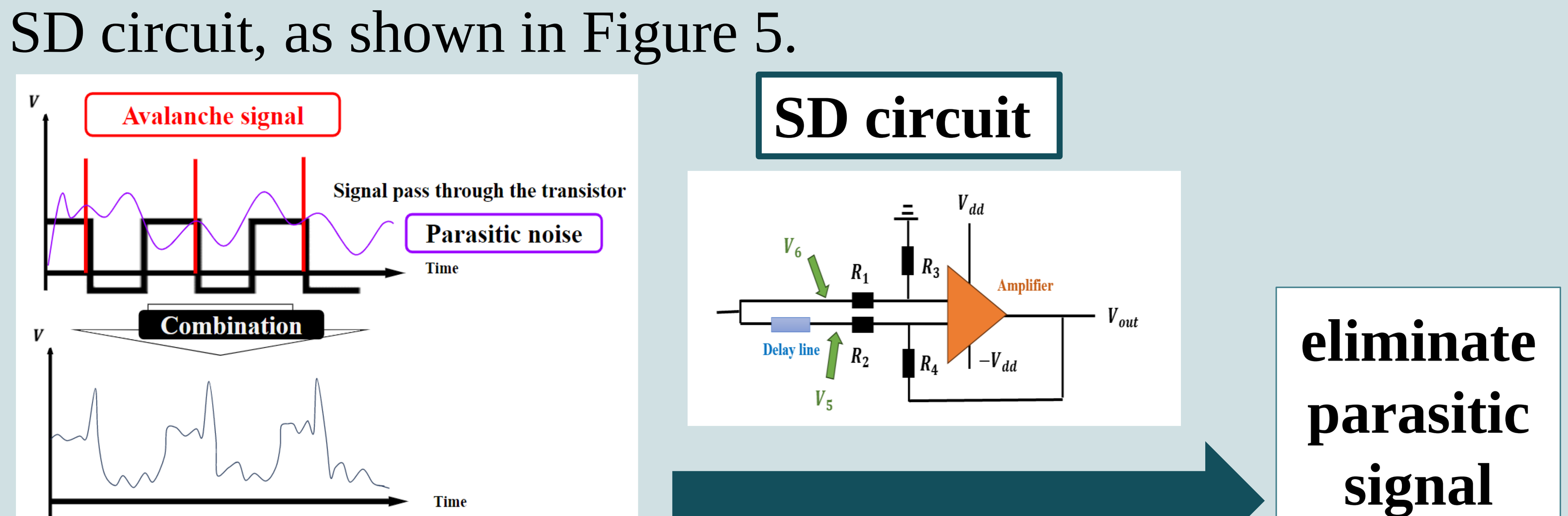

Fig. 5 The operaton of SD circuit

Results

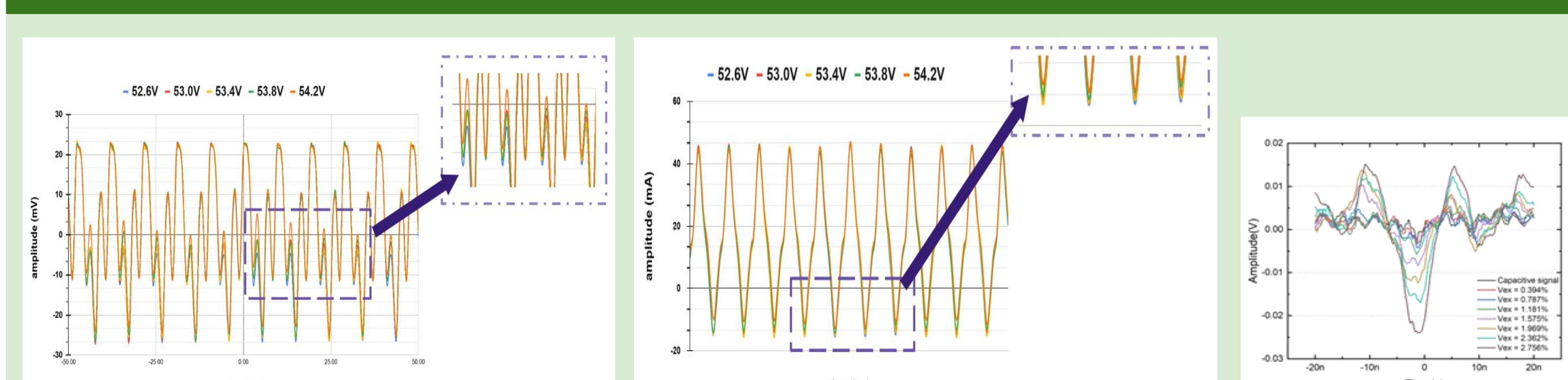

Fig.6 At room temperature, without light illumination (a) PQAR without SD (b) PQAR with SD (c) PQC with SD

By increasing the DC bias, I investigated the breakdown behavior. While the signals without SD showed periodicity, the presence of substantial parasitic noise made interpretation challenging. SD circuit significantly reduced the parasitic noise. Compared to PQC circuit with SD, PQAR circuit demonstrated a more distinct breakdown signal, facilitating analysis.

Conclusion

A PQAR circuit operating in gated mode with positive bias is designed and analyzed in this study. The circuit demonstrates excellent waveform shaping and dynamic adjustment capabilities, as confirmed by simulation and measurement. To address the phase shift caused by high-frequency operation, calibration is performed. Furthermore, the adoption of a SD circuit significantly reduces parasitic noise, enhancing the clarity of the breakdown signal.