Unlocking Ultra-Fast TCSPC: An Integrated Readout Circuit for a 3D Digital Silicon Photomultiplier

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The detection of single-photons with high temporal resolution has played a primary role in biomedical imaging through Time-Correlated Single-Photon Counting (TCSPC). Although conventional TCSPC enables precise analysis of fast and faint optical signals, its acquisition rate has historically been limited to a small fraction of the laser repetition rate to avoid pile-up distortion [1]. In 2023, constraint-free TCSPC was introduced [2], demonstrating that tracking the activity state of the photon detection system can enable TCSPC operation at unprecedented count rates. In particular, when the detector dead time is short, this method allows the acquisition of multiple photons per period with negligible distortion. In this context, digital Silicon Photomultipliers (dSiPMs) are promising devices, combining the fast timing response of Single-Photon Avalanche Diodes (SPADs) with the multi-photon detection capability of SiPMs. Furthermore, 3D stacking of the detector and readout minimizes parasitic capacitance and inductance in each SPAD-readout connection. In this work, we present a fast integrated readout circuit prototype (Fig. 1) for a Mini-3D-dSiPM composed of 9 SPADs, where the number of SPAD cells results from an optimization algorithm targeting both short dead time and multi-photon detection capability. Designed in *55-nm* BCDLite technology, the circuit quenches macroscopic avalanche currents using high-voltage transistors while low-voltage devices implement fast digital logic. Photon arrival times are extracted by serializing the signals from the 9 SPADs through a fast 9-input OR gate, achieving a post-layout dead time as short as 400 ps while minimizing the number of output pads and system complexity. Moreover, the synchronous reset feature allows monitoring of the activity of the array to account for fired cells during each measurement period, ensuring accurate photon detection in constraint-free TCSPC. This architecture enables recording multiple photons per period, bringing TCSPC closer to real-time deployment and extending its intrinsic precision to practical biomedical applications.

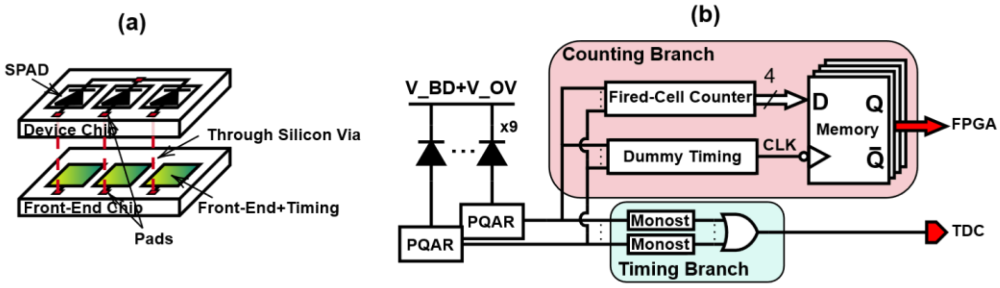

Fig. 1: *(a) structure of the 3D-dSiPM photodetector; (b) block diagram of the front-end*

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References

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[2] Rech, I. et al. (2023). Toward Constraintless Time-Correlated Single-Photon Counting Measurements: A New Method to Remove Pile-Up Distortion. *IEEE Journal of Selected Topics in Quantum Electronics*, 30(1), 1-12.