Study on FPGA-Based Real-Time Signal Processing for SOI MOSFET Single-Photon Detector

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学 位 論 文 要 旨

Abstract of Doctoral Thesis

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論文題目：SOI MOSFET 単一フォトン検出器のための FPGA に基づく実時間信号処理の研究
Title of Thesis：Study on FPGA-Based Real-Time Signal Processing for SOI MOSFET Single-Photon Detector

論文要旨：
Abstract：
In recent years, a remarkable performance of single-photon detectors over a wide spectral range provokes extensive applications in fluorescence measurement, medical imaging such as positron-emission tomography (PET), light detection and ranging (LiDAR), quantum cryptography, optical-time domain reflectometer, etc. These wide range of applications place a dramatic increase in interest in single-photon detection. Such applications require some of the combined following properties such as large maximum count rate (MCR), small dark count rate (DCR), high quantum efficiency (QE), high photon number resolution (PNR), etc. An intensive research has been made for better performance and new unique functionalities. The main objective of this work is to develop a novel signal processor for silicon-on-insulator (SOI) MOSFET single-photon detector. In case highly sensitive electrometers, such as single-electron transistors (SET) and scaled-down FET, are adopted, photogenerated charge or photoinduced polarization can be detected one by one without multiplication. This approach led to an impressive improvement in the properties of the detector. The SOI MOSFET single-photon detector with gate length of 70 nm and channel width of 110 nm used in this study operates at room temperature and features low dark count rate (~ 0.01 s^{-1}), photon-number resolution and small operation voltage (~ 1 V) in contrast to the conventional single-photon detectors such as photomultiplier tubes (PMTs) and avalanche photodiodes (APDs). Photogeneration and recombination of holes modulate the channel electron current and can be detected as pulses. However, such a signal generation mechanism results in complex output waveforms consisting of rising and falling edges corresponding to photogeneration and spontaneous recombination of holes. The randomness in the waveform of the detector can be understood as the statistical fluctuation of the hole generation and recombination, which follows the Poisson process. Multiple signal levels reflecting the amount of accumulated holes can be caused by the hole lifetime longer than the hole generation interval set by the photon incident rate and the light absorption efficiency. To resolve the above-mentioned issues, signal processor is essential to detect the rising edge and give an output short pulse, whose height is proportional to the step

height. In this thesis, a real-time signal processor is demonstrated, and the statistical distribution is studied in detail. To verify the operation of signal processor at a wavelength of 535 nm, the detector output waveforms at different light intensities are processed. The signal processing algorithm is implemented in field programmable gate array (FPGA) for real-time usage as it supports the high data rate. The experimental results suggest that the number of photogenerated holes and their timings are promptly examined. The signal processor can properly extract the photon incidence information in real-time. In the later part of the thesis, the generalized performance of photon detector based on single-charge counting, including that of the SOI MOSFET detector, is estimated in terms of DCR and MCR. Based on the linearity between detected and generated rates of holes, and detected rate under null generation for different noise levels and sampling frequencies, correlation between MCR and DCR is established for a given charge sensitivity. From the simulation result, the state-of-the-art charge sensor can realize DCR of 0.01 s^{-1} and MCR of 6.60 Ms^{-1} with a high dynamic range of 176 dB. It could be attained by the charge sensitivity (δQ) of 1×10^{-5} e/√Hz, under the condition that the bandwidth (BW) is 139 MHz and sampling frequency (f_s) is 277 MHz. The performance of detector by simulation is quantitatively correlated to the experimental results. The linear relationship is found between a light intensity and the hole generation rate. The MCR and δQ of the SOI MOSFET single-photon detector are ~ 300 and ~ 800 counts/second (bandwidth of current preamplifier is 800 Hz and 4 kHz respectively) and ~ 3×10^{-3} e/√Hz respectively. Based on the detector active area (1.07 μm × 0.11 μm) and from experimental data, the nominal QE is calculated to be 0.18 %. The low QE is caused by the opaque upper gate (UG) of the detector and the thin SOI layer. It could be improved by replacing the UG with a transparent one and/or introducing the optical antenna. Finally, the frequency response of present detector is evaluated. Since the operation of the single-photon detector in this study is limited by the bandwidth of the current preamplifier (800 Hz), the possible primary way to improve the MCR is to increase the charge sensitivity of the device. The secondary method is to widen the bandwidth of the current pre-amplifier or to integrate the higher bandwidth on-chip preamplifier if the wiring limits the bandwidth. In present study, the bandwidth of the device is limited by the current preamplifier. Considering the overall results, the developed signal processor can be a promising solution to resolve the issue of complex detector output waveforms. The direction to improve the performance of the detector is discussed. Once if the speed (MCR) and QE are enhanced, detector together with signal processor is a promising candidate in imaging under a very week light application. It is also expected that the developed signal processor can be applicable to various single-charge counting photon detectors for the wide spectral range from submillimeter waves to visible lights, such as quantum dot (QD) detectors, QD-gated FET, charge-sensitive infrared phototransistor (CSIP), QD optically gated FET (QDOGFET), etc., and surely give a large impact on expanding their usage.