Single-photon Counting System Based on a 4H-SiC Avalanche Photodiode

Fei Liu*, Leng Zhang and Fangzheng Li
School of Electronics and Information Engineering, Jinling Institute of Technology, Nanjing 211169, China
*Corresponding author’s e-mail: liufei2013@jit.edu.cn

Abstract. Weak ultraviolet (UV) signal detection systems have broad application prospects in fields such as space science, aerospace, and military communications. 4H-SiC avalanche photodiode (APD) devices have a high internal gain and can be used in single-photon-based UV radiation counting systems when in Geiger-mode operation. The system comprises an APD drive circuit, a passive quenching circuit, a signal conditioning circuit, a counting and control circuit based on a microprogrammed control unit, and a display module, which can perform real-time monitoring of changes in weak UV radiation.

1. Introduction
At the start of 2020, pneumonia caused by a novel coronavirus (COVID-19) broke out across many places in China[1]. Owing to its long incubation period and high infectivity, it quickly spreads to numerous countries around the world, severely damaging people’s production and life as well as international communications. The National Health Commission of China has repeatedly issued novel coronavirus pneumonia prevention and control programs, clearly stating that the novel coronavirus belongs to the genus Beta-coronavirus and is very sensitive to UV light; hence, the virus can be inactivated under the exposure of UV disinfection lamps[2-4]. However, the UV wavelength currently used for disinfection is mostly 254 nm, which is harmful to normal human cells. Direct UV exposure to the skin can cause redness, swelling, pain, and even severe diseases such as skin cancer. Therefore, ensuring that the UV radiation intensity is below a safe threshold with human presence is critical. Besides, the high-voltage condition in the drive circuit of UV disinfection lamps may reduce the emitting power due to aging, surface contamination, and other reasons, so virus inactivation may not be achieved[5]. The above-mentioned problems demand to be solved by incorporating appropriate sensors in the UV disinfection system to monitor the intensity of UV radiation.

To perform real-time monitoring without affecting the disinfection efficiency of UV LEDs, sensors should be placed on the side face of the UV direct light path instead of being placed in the light path. The intensity of UV light is monitored by the scattering effect of UV light in the atmosphere. Because the UV radiation scattered on the sensor is extremely weak, a single-photon counting system based on the 4H-SiC avalanche photodiode (APD) operating in Geiger mode was designed in this paper. Our proposed counting system can count the pulse voltage caused by the incidence of photons, thereby achieving the detection of extremely weak UV radiation.

2. Structure and characteristics of 4H-SiC APD
This system adopts an APD sensor based on 4H-SiC multilayer epitaxial material prepared by Nanjing...
University. It has a PIN structure with N-type 4H-SiC as substrate, and from bottom to top are the N-region contact layer, weak P-region composite layer, heavily doped P-region layer, and P-region contact layer. To diminish non-uniformity of the electric field at the edge of the mesa, an inclined mesa was prepared by high-temperature reflow technology and inductively coupled plasma (ICP) etching. The etching damage was removed by thermal oxidization at 1050°C.

A Keithley 2450 source meter was used to measure the I–V characteristics of the 4H-SiC APD. The output voltage and current acquisition were controlled via a LabVIEW program. Its dark current and photocurrent characteristic curves are illustrated in Figure 1. The light source was provided by a 280-nm UV LED. This figure shows that before the avalanche breakdown, the dark current of ADP was very low; but from 180 V, both the dark current and photocurrent increased sharply, indicating that the device has an avalanche breakdown around 180 V.

![Figure 1 I–V curve of 4H-SiC APD](image)

3. Principle of single-photon counting

Due to the absorption and scattering by the atmosphere, the UV radiation that can reach the photosensitive surface of the photodetector is extremely weak and the generated photocurrent is even smaller than the thermal noise of the photodetector itself. Therefore, the traditional photocurrent detection method cannot extract the optical signals from the noise. Meanwhile, UV radiation exhibits quantum properties. Thus, when the radiation reaches a certain weakness, it will be incident on the photodetector in the form of a discrete single photon. If a 4H-SiC APD device with a sufficient reverse bias (the structure is shown in Figure 1) is used, there will be a very large electric field in the PN junction region. The electron–hole pairs created by photon incidence will drift and accelerate toward the two ends as driven by the electric field. Once obtained enough energy, they will hit the lattices and create new electron–hole pairs. As this process continues, a very large current will be generated, which is known as the avalanche effect [6]. Simultaneously, the passive quenching circuit illustrated in Figure 2 is used to collect avalanche signals and avoid device damage caused by excessive current. Its working principle is as follows: When an avalanche breakdown occurs in the APD, the current passing through the APD increases rapidly, and the voltage drop on the large series resistor R_L also increases continuously. Hence, the working voltage across the APD is gradually reduced to below the avalanche breakdown voltage of APD, thereby quenching the avalanche. Subsequently, the internal capacitance of the APD is charged, so that the working voltage of the APD is raised again above the avalanche breakdown voltage to achieve the next avalanche breakdown. In this circuit, the source meter is the Keithley 2450, and the voltage on R_s is acquired using the Tektronix DPO4032 oscilloscope[7].
Figure 2. Passive quenching circuit diagram.

Figure 3. Voltage pulse

Figure 3 is a typical voltage pulse recorded by an oscilloscope, demonstrating that the pulse height can reach hundreds of mV and can be counted effectively using discrimination techniques. Each pulse represents the signal of one incident photon; the intensity information of the incident UV radiation can be obtained by counting the number of photons per unit time.

4. Key circuit design on the board-level

The instrument-based passive quenching circuit illustrated in Figure 2 can achieve single-photon detection. However, due to its high cost and bulk size, it can only be used in a laboratory environment. To reduce costs and expand its application fields, a single-photon counting system was developed based on the board-level circuits[8]. As shown in Figure 4, a reverse bias voltage is added on the electrodes of 4H-SiC APD, which works in the Geiger mode. When a photon is incident, the voltage pulse signal is generated, as shown in Figure 3. After amplification by the amplifying circuit, the signal was input into the comparison circuit and compared with the preset threshold voltage. Only when the amplitude of the input pulse is greater than the threshold voltage, a square pulse signal with an amplitude of 5 V will be output. The square pulse signals are counted by an MCU that can acquire the number of effective incident photons per unit time to characterize the UV radiation. Meanwhile, as the control core, the MCU will display the detection results and necessary information on the screen as well as adjust the bias voltage of APD and the threshold voltage of the comparison circuit. The system comprises four parts: a drive and quenching module, signal conditioning module, counting and control module (based on MCU), and display module.

Figure 4 Block diagram of the photon counting system
4.1 Drive and quenching module

As shown in Figure 2, the avalanche voltage of 4H-SiC APD is approximately 174 V, and the photoelectric response is closely related to the bias voltage applied; therefore, an adjustable high-voltage power supply with an input voltage of 12 V and a maximum output voltage of 200 V is adopted for driving the APD. The digital-to-analog converter (DAC) of the MCU can output an analog voltage of 0–3.3 V to the Vcon-in port of the adjustable high-voltage power supply; thus, a suitable driving voltage can be obtained. RL is the quenching resistor, RS is the acquisition resistor, and the OUT port outputs APD pulse signals to the subsequent circuit.

4.2 Signal conditioning circuit

In the design of the single-photon counting system, the APD outputs discrete pulses with amplitudes ranging from tens to hundreds of millivolts, which cannot fulfill the input requirements of the counting system. Therefore, conditioning the signal by designing an amplifying circuit with a certain gain and bandwidth as well as a comparison circuit for shaping and discrimination is necessary. We chose OPA322 from TI as the preamplifier; it is a rail-to-rail amplifier with extremely high input impedance that can effectively couple avalanche signals. The peripheral circuit is added, and the amplification factor of the amplifier is set to be 10, which can amplify the voltage signal to the volt level for the convenience of the comparator. The amplifier uses a negative feedback amplifying circuit. AD8611 serves as the comparator. The avalanche pulse signal is input by IN+; in the meantime, the threshold voltage (adjustable) preset by MCU via DAC is input at IN-. Comparing these two values, if the signal level is higher than the reference voltage, QA outputs a high level; otherwise, it outputs a low level. Output signals are derived from QA, and pulse signals with an amplitude of 5 V can be obtained, which are convenient for the digital pin recognition of MCU.

4.3 Counting and control module

The MCU-based counting and control module is the core of the UV photon counting system. It not only counts the square pulse signals that have been amplified and shaped by the comparator but also outputs
and controls the signal level required by the system. The input capture mode is used for the counting function; namely, the pulse signal is connected to the P0 interface, and when an edge signal transition is detected (the rising edge is used in this system), it is recorded in the set count register. After the timer reaches the unit time, the value of the count register is output and cleared to start the detection of the second cycle. The control function is mainly divided into three parts: APD bias control, comparator threshold control, and display module control. The APD bias control voltage is output by DAC1. To protect the APD device, a progressive method is used to gradually increase the output bias voltage to the avalanche voltage. Owing to the inhomogeneity during production and processing, there is a certain deviation in the avalanche voltage of each APD; therefore, a fixed dark count, instead of a fixed bias voltage, was used as the determination criterion; this was also helpful for subtracting the background during the measurement. The comparator threshold voltage control is performed by DAC2 with a preset value of 1 V, and it can be manually adjusted with keys according to the sensitivity requirements. The DAC output of the MCU does not match the input impedance of the high-voltage power supply and the comparator, so a voltage follower is used for conversion. The control of the display module is detailed in the next section.

5. Experimental results
A 280-nm UV LED serves as the light source to verify the photoelectric response and reliability of the UV counting system. The parameters of UV LED are shown in Table 1:

| Applicable Wavelength | Working Current | Voltage Range | Beam Angle | Power |
|-----------------------|-----------------|---------------|------------|-------|
| 280 nm                | <20 mA          | 5.0–7.0 V     | 7°         | 1.5 mW|

The light intensity is changed by adjusting the current of LED, and the system is calibrated using standard silicon devices. Figure 7 is the photoelectric response curve of the UV photon counting system. The horizontal axis is the output light intensity of the UV light source, and the vertical axis is the light pulse count value of the APD. The result shows that as the light intensity increases, the count value of the system increases linearly. According to Figure 7, the UV light intensity in the system area can be quickly calculated from the count value on the display interface, thereby determining whether an effective disinfection effect can be obtained and the harm to the human body in this area.

\[ I(\mu J) = k \times PCR(\text{kHz}) \] (1)

k is a conversion factor, which is approximately equal to 0.02, according to Figure 7.

The UV photon counting system is exposed to high-energy UV photon irradiation for considerable time, which involves the complex process of carrier generation and recombination inside the semiconductor. Thermal noise, low-frequency noise, and its unique avalanche noise may cause...
measurement errors; hence stability is one of the criteria for judging system performance. This paper recorded the system signal output in a certain time period with or without UV light. As shown in Figure 8, the system is relatively stable, as the data error is less than 4%, and there is no obvious unidirectional trend. The average method or the median filter method can also be applied to further reduce the measurement error.

6. Conclusions
Based on the single-photon detection characteristic of the 4H-SiC APD device, a UV photon counting system applicable for practical detection is designed in this paper. The system uses 4H-SiC APD as the key detection device and an adjustable high-voltage module as the drive circuit. The signal of APD is amplified to the 100mV magnitude, and then input MCU for counting and display. Meanwhile, as the control core, MCU is suitable for adjusting the avalanche voltage of APD and the threshold voltage of comparator. The results demonstrate that the system has high linearity and good stability for weak UV radiation detection, thereby being useful for single-photon detection in different scenarios.

References
[1]. Zhou P, Yang XL, Wang XG. (2020) A pneumonia outbreak associated with a new coronavirus of probable bat origin. Nature 579(7798): 270-273.
[2]. National Health Commission of the People’s Republic of China, (2020) Novel Coronavirus Pneumonia Prevention and Control Programme (5th edition)
[3]. Cadet, J., & Douki, T. (2018). Formation of UV-induced DNA damage contributing to skin cancer development.. Photochemical and Photobiological Sciences, 17(12), 1816-1841.
[4]. Chen K. (2018) Study on Virus Inactivated DBJ by UV irradiation. School of Guangdong Pharmaceutical University.
[5]. Eickmann, M., Gravemann, U., Handke, W., Tolksdorf, F., Reichenberg, S., Müller, T., & Seltsam, A. (2018) Inactivation of Ebola virus and Middle East respiratory syndrome coronavirus in platelet concentrates and plasma by ultraviolet C light and methylene blue plus visible light, respectively. Transfusion, 58(9), 2202-2207.
[6]. Yan, F., Qin, C., Zhao, J. H., Bush, M., Olsen, G. H., Ng, B. K., ... & Weiner, M. (2003). Demonstration of 4H-SiC avalanche photodiodes linear array. Solid-state Electronics, 47(2), 241-245.
[7]. Zhou, D., Liu, F., Lu, H., Chen, D., Ren, F., Zhang, R., & Zheng, Y. (2014). High-Temperature Single Photon Detection Performance of 4H-SiC Avalanche Photodiodes. IEEE Photonics Technology Letters, 26(11), 1136-1138.
[8]. Fei, L., Dong, Z., Hai, L., Dunjun, C., Fangfang, R., Rong, Z., & Youndou, Z. (2015). Passive Quenching Electronics for Geiger Mode 4H-SiC Avalanche Photodiodes*. Chinese Physics Letters, 32(12), 128501-128501.