Study on non-linearity response of 4H-SiC APD

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

Abstract. UV photon counting detection technology based on 4H-SiC Avalanche photodiodes (APDs) has been widely used in virus inactivation system, quantum communication and other UV detection fields. When the ultraviolet signal is enhanced, the detection accuracy will also decrease due to the nonlinear characteristics of the photoelectric response. Therefore, the physical mechanism and nonlinear error source of the photoelectric response of 4H-SiC APD were analysed, and a photoelectric response characteristic testing system was built. The theoretical and experimental results show that the photocurrent increases linearly when the incident photon number is high, and the multi-photon incident results in the nonlinear phenomenon of photon count. Reducing device bias and increasing threshold voltage can significantly improve the nonlinear phenomenon of photoelectric response, and the maximum linear operating range of the device can be extended from $10^7$s$^{-1}$ to more than $10^9$s$^{-1}$.

1. Introduction
In recent years, ultraviolet (UV) detection technology has attracted much attention from both industry and academics owing to its potential applications such as corona discharge, environmental monitoring, flame detection, chemical/biological agent detection and covert space-to-space communication [1-3]. Among these applications, UV single photon counting detection for capturing faint UV signals down to tens or even single photon in short time is required. Avalanche photodiodes (APDs) are being intensively studied as a replacement for Photomultiplier tubes (PMTs) which are the most popular UV detectors to be used in weak UV detection due to its unique advantages of high internal gain, fast timing response, small size and single-photon response [4]. Although APDs based on group-III nitrides have the benefit of adjustable spectral response for solar-blindness, the high defects density in (Al)GaN material system still result in premature breakdown and high dark current. Comparatively, 4H-SiC is a more appropriate semiconductor for APD fabrication as it could simultaneously offer excellent material quality, lower defect density [5-7].

With the development of crystal growth and device processing technologies, several groups have successfully fabricated 4H-SiC APDs and realized single photon detection. Electrical and optical characteristics of APD such as dark/photo current, gain, dark count rate (DCR), single photon detection efficiency (SPDE) have been reported [8-9]. However, until recently, the performance of 4H-SiC APD is only characterized by invariable light source, while for many critical applications, linearity of the photodiode response to the UV incident luminous flux is important to study [10-11].

In this work, the 4H-SiC APD with high multiplication gain and low dark count rate is fabricated and characterized under dark and light conditions. The different levels of UV illumination are obtained by a GaN 280 LED with variable operating current. The linearity of photo-current and single photo counting performance of 4H-SiC to incident photon rate are studied as correlates of bias voltage and
discrimination voltage.

2. Photodiode structure and fabrication

The 4H-SiC APD with position bevel mesa studied in this work is fabricated using standard silicon processing techniques. As shown in fig.1, the APD structure is grown on n-type 4H-SiC substrate, which consists of four epitaxial layers: a 2.0 μm n+ layer, a 0.6 μm p- layer, a 0.2 μm p layer, and a 0.1 μm p+ layer. The doping concentrations of the these layers are $1 \times 10^{19}$ cm$^{-3}$, $3 \times 10^{15}$ cm$^{-3}$, $2 \times 10^{18}$ cm$^{-3}$, and $2 \times 10^{19}$ cm$^{-3}$, respectively. The 4H-SiC was partially etched to form position bevel mesas with a bevel angle of ~4° and a 900nm mesa height. To improve the electric field quality along the mesa surface, The APD is passivated by a combination of thermal oxidation in dry O$_2$ at 1050°C and SiO$_2$ deposition by using plasma-enhanced chemical vapor deposition at 350 °C. Next, p-type and n-type ohmic contacts both based on Ni/Ti/Al/Au (35 nm/50 nm/200 nm/100 nm) metal stack are deposited by e-beam evaporation, followed by rapid thermal annealing (RTA) in N$_2$ ambient at 850 °C for 3 min. Finally, thick metal pad layer based on Ti/Au (800 nm/200 nm) bi-layer is deposited for easy electrical probing.

![Fig.1. Cross sectional schematic of the 4H-SiC APD](image)

3. Experimental results:

The current-voltage (I-V) characteristics of the 4H-SiC APD were performed in dark and light environment by using a keithley 2450 sourcemeter. A 280 nm GaN LED was used to provide the UV illumination in this work. For bias below 155 V, the 4H-SiC APD shows very low dark current which less than 0.1 nA as shown in Fig.2. The dark and photo current both exhibit an abrupt breakdown while bias voltage increases to ~186V, which is marked as breakdown voltage.

Another feature in Fig.2 that shows the influence of the bias voltage on avalanche gain M. Here M can be described by the following equation:

$$M = \frac{I_{PM} - I_{DM}}{I_P - I_D}$$

where $I_{PM}$ is the multiplied photo current, $I_{DM}$ is the multiplied dark current, while $I_P$ and $I_D$ are the unmultiplied photo dark current, respectively. If the unity gain ($I_{PM} = I_P$, $I_{DM} = I_D$) is defined at bias voltage of 25V, the gain measured in this experiment can reach up to $10^5$. The actual multiplication gain should be even higher, as a photocurrent limit of $10^{-5}$A for the APD is pre-set by the sourcemeter to avoid self-heating.
Because of the higher gain, the current of APD under the high bias voltage was bigger than ordinary p-i-n device for it inject light. The photocurrent is studied as function of UV intensity using a controlled 280nm LED light source with a series of forward current. The photo-current (P-I) characteristics of APD are plotted on double logarithmic scale in Fig.2. It is quite clear that the current varies as $P^m$ in specific optical injection regime. The response can be considered almost perfectly linear ($m=1$) up to an incident rate of $10^7$ photons/s, while bias of APD is $187.1 \text{ V}$). At high-count rate, the photo-current response change to sub-linear dependence of $I$ on $P$ ($m=0.7<1$). The parameter $m$ reflects the effect large injection of on the avalanche processes.

The single photon counting performance of the 4H-SiC APD is characterized by using a passive quenching circuit as shown in Figure 4. $V_B$ is set to a value above the breakdown voltage of 4H-SiC APD. Before avalanche event is triggered by absorption of a photon, just dark current is flowing through load resistance ($R_L$) and sampling resistance ($R_S$), making the bias voltage of APD to be approach to $-V_B$. After the absorption of a photon, avalanche current flows through the resistances, make the voltage of APD reduce to $V_B-I(R_L+R_S)$, then avalanche is quenched. A Tektronix DSO4032 oscilloscope is used to record the pulse waveform of $R_S$.

A few low avalanche pulses occur even no UV photon be absorption by APD in dark environment, as illustrated in Fig.5(a). These pulses called dark count are caused by the thermoelectric in semiconductor. Fig.5(b) presents the characterization of avalanche pulses captured by the oscilloscope change obviously upon weak UV illumination, including quantity and height distribution. Clearly the photon pulses become more intensive and higher than dark pulses. Therefore, UV intensity is characterized by quantity of pulses above threshold voltage using our 4H-SiC APD and passive quenching circuit. If the higher threshold voltage is chosen, more dark count pulses would be filtered.
out while photon count pulses have less effect.

As the LED becomes brighter, total pulses count in Fig.5(c) increases while tall pulses above threshold voltage maybe decrease. Photon count rates is not linearity monotonic function as the number of incident UV photons. The explanation of this nonlinearity effect is that the 4H-SiC APD is detecting UV photons faster than its quenching-recharging rate. There is a period of time between the 4H-SiC APD recharging to just above breakdown voltage and the bias of 4H-SiC APD reaching $V_B$. If the mean time between photon absorptions is less that the time necessary to recharge the APD fully to $V_B$, then the lower voltage beyond breakdown of the APD will result in lower pulse.

![Fig.6. 4H-SiC APD nonlinearity of response at different threshold voltage](image)

![Fig.7. 4H-SiC APD nonlinearity of response at different bias](image)

More details of nonlinearity response of single photon detection based 4H-SiC APD are reported in Fig.6, in which the pulses count is represented as a function of the rate of photons impinging on the APD active region. The bias voltage of APD is set at 180.9V and a series of UV photons counts rates from $10^6$ to $10^9$photons/s are offered by a controlled LED. As shown in Fig.6, the electronic pulses count varies as $P^m$ in specific optical injection regime, just like fig.3. Where P is photons rate and m is the slope of curve on double logarithmic scale. The curves present two distinct parts, take the curve which threshold voltage is 50mV for example, one in which m is a constant (0<m<1) and the pulses count increases as a sub-linearity function of photons rate; a second in which m is decrease from a positive constant to zero to negative values and the pulses count is nonlinearity and non-monotonic function of photons rate. Another feature in Fig.6 that reveals the influence of the photons rate on pulses count is the nonlinearity and non-monotonic effect can be improved by lowering threshold voltage.

![Fig.7 shows the influence of bias voltage on the nonlinearity and non-monotonic effect of the photo-electronic response. It is found that higher bias voltage of passive quenching circuit can improve the nonlinearity and non-monotonic effect. The threshold voltage is set at 40mV and the bias voltage rises from 180.7V to 181.1V, the monotonic range increases from $\sim 10^7$ photons/s to at least $10^9$ photons/s.]
4. Conclusion:
In summary, a 4H-SiC APD with low dark current and high avalanche is designed and fabricated for single counting detect application. Characterization of Electronic-photon response is studied by passive quenching circuit and controlled 280 nm UV LED. Since the incident photons faster than APD recharge rate, the nonlinearity and non-monotonic effect becomes dominant at high photons rates. Lower threshold voltage and higher bias voltage can improve the monotonic range from $10^7$ to $10^9$ photons/s.

Acknowledgement:
This work was supported by the Natural Science Foundation of the Jiangsu Higher Education Institutions (19KJD470001).

References:
[1] Razeghi, M. Short-wavelength solar-blind detectors-status, prospects, and markets[J]. Proceedings of the IEEE, 2002, 90(6):1006-1014.
[2] Shaw, GA, Siegel, AM, Model, & Greisokh. (2005). Recent progress in short-range ultraviolet communication. P SOCIETY PHOTO-OPT INSTRUM ENG, 2005,5796(-), 214-225.
[3] Campbell J C , Demiguel S , Feng M , et al. Recent advances in avalanche photodiodes[J]. IEEE journal of selected topics in quantum electronics, 2004, 10(4):p.777-787.
[4] Fei Liu, Dong Zhou, Hai Lu et al. Passive Quenching Electronics for Geiger Mode 4H-SiC Avalanche Photodiodes[J]. Chinese Physics Letters, 2015, 32(12):128501.
[5] Xiaolong Cai , Chenfei Wu , Hai Lu , et al. Single Photon Counting Spatial Uniformity of 4H-SiC APD Characterized by SNOM-Based Mapping System[J]. IEEE Photonics Technology Letters, 2017, PP(19):1-1.
[6] Huili Zhu, Xiaping Chen, Zhengyun Wu. A study of p-type Ohmic contact for 4H-SiC avalanche photodetector[J]. Chinese Journal of Quantum Electronics, 2007, 24(6):743-747.
[7] Xingye Zhou, Xin Tan, Yuangang Wang et al. High-performance 4H-SiC p-i-n ultraviolet avalanche photodiodes with large active area[J]. Chinese Optics Letters, 2019, v.17(09):5-8.
[8] Vert, A, Soloviev, et al. Solar-Blind 4H-SiC Single-Photon Avalanche Diode Operating in Geiger Mode[J]. Photonics Technology Letters, IEEE, 2008, 20(18):1587-1589.
[9] Beck A L, Karve G , Wang S , et al. Geiger mode operation of ultraviolet 4H-SiC avalanche photodiodes[J]. IEEE Photonics Technology Letters, 2005, 17(7):1507-1509.
[10] Gran, M, E. R. Pike, and E. Pailharey . Non-Linearity of APDs at High Count Rates. Springer Netherlands, 1997, 40(7) 117-127.
[11] Nada M , Yamada Y , Matsuzaki H . A High-linearity Avalanche Photodiodes with a Dual-carrier Injection Structure [J]. IEEE Photonics Technology Letters, 2017, PP(21):1-1.