4H-SiC Single Photon Avalanche Diode for 280nm UV Applications

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1. Introduction

UV detectors covering the solar blind spectrum region of 280nm have many medical, space and military applications including compound identification, NLOS communications, missile and aircraft detections because above the solar blind spectrum there is an intense background solar radiation at wavelengths longer than ~290nm and there is strong atmosphere scattering and ambient absorption below ~270nm. Qualified detectors in solar blind spectrum region often need a high quantum efficiency (QE), a high UV to solar rejection ratio, a fast response, and a high reliability under harsh environments such as high radiation and large temperature variations. The intensity of interesting UV signals in solar blind region is usually extremely weak, implying the need for very high-sensitivity detectors. Therefore, single photon avalanche diodes (SPADs) have the best potential to provide the required gain and speed simultaneously to sense these weak signals with their quantum-limit-approaching capability. In recent years, state-of-the-art Si SPADs have been developed with very high detection efficiency (>60%) in the visible wavelength region and very low dark count rate (DCR) (<1kHz) for very small size detectors. However, four major factors limit the Si SPADs for UV detections. First, the shallow light penetration depth around 280nm in Si results in a poor quantum efficiency. Also Si SPADs need short pass filters blocking a wide spectrum from infrared to visible for UV detections. Up to date, no UV Si SPADs operating at Geiger mode are reported. In addition, the size of Si SPADs is limited (d≤30um) because of the thermal generation of carriers when operating at room temperature, and larger size SPADs always require cooling for a low DCR. Finally, harsh environments will cause damages in Si SPADs. NASA recently reported a 55.5counts/day DCR increase for Si SPADs in a near-earth orbit satellite due to cosmic rays (such as mega eV protons) and a huge DCR increase of 2500cts/s per device in a solar storm [1]. These material limitations are fundamental to Si. SiC is substantially more tolerant to harsh environment. The first SiC SPAD was reported in early 2005 [2] and excellent progress has been made subsequently [3]. In this paper, we present a 4H-SiC SPAD with a high single photon detection efficiency (SPDE) of 9.73% with a DCR of 91kHz and of 5.65% with a low DCR of 22kHz at the solar blind wavelength of 280nm.

2. Fabrication and Characterization

Fig. 1 is the top view and cross sectional view of the SiC SPAD. It consists of a p+ contact layer, a p layer, a p- depletion layer and an n buffer layer on the n+-type substrate. The p- depletion layer is 0.3μm thick with a light doping of $3\times10^{14}\text{cm}^{-3}$. The device structure was continuously grown in an Epigress VP508 using silane and propane chemistry with nitrogen and aluminum dopants. The device edge is terminated by a positive bevel formed by inductance coupled plasma (ICP) dry etching. The bevel passivation is accomplished by a 3-hour thermal oxidation at 1050°C, followed by another PECVD deposition of 0.4μm SiO_2 and 0.15μm Si_3N_4. Backside n-type ohmic contact was formed by annealed Ni alloy. Top p contact metal is sputtered and annealed to form an ohmic contact to the top p+ layer. The optical window has a diameter of 50μm.

Fig. 2 shows the reverse I-V and gain characteristics. An ultra-low leakage current of less than 20fA is achieved at unity-gain. The breakdown voltage (V_{BR}) is 114V. At the 90% of V_{BR} the leakage current is 57.2fA. At a reverse bias of 116.8V, the linear mode gain can easily reaches 1.4×10^6. These SiC SPADs have a very good UV-to-visible rejection ratio, for example the the QE at 280nm and 400 nm are 29.8% and 0.0070%, respectively. The rejection ratio of UV to visible light is 4.3×10^3. Single photon counting measurements are performed in a passive quenching circuit shown in Fig. 3. The SPAD is DC biased to the breakdown voltage using a Keithley 6517A electrometer. A UV LED with output peaked at 280nm is used as the photon source. The incident photon flux is measured to be 15photons/μs. Output voltage signals are collected through a 200Ω load resistor using a Tektronix

DPO 4032 oscilloscope. Each measurement records 4msec data with a sample rate of 2.5Gs/sec. Fig. 4 shows the dark counting and photon counting spectra at the bias of 116.8V. The number of dark counts decreases dramatically with the increase of the photon counting threshold voltage (V_{th}). We find that when the threshold voltage varies from 10mV to 18mV, the DCR drops from 91kHz to 22kHz, and the corresponding SPDEs are equal to 9.73% and 5.65%, respectively, which corresponds to a counting efficiency (CE) of 18.9% and 32.7%, considering that the QE at 280nm is 29.8%.

Although the optical window size of the SPAD, $1.9\times10^3\mu m^2$, is already much larger than typical Si SPADs, it is only 10% of the junction area, and >60% of the top mesa is occupied by the bonding pad that has no contribution to the photon counting. The SPAD's a low DCR of 22kHz at 116.8V and V_{th} = 18mV corresponds to a very low normalized DCR of $1.2 Hz/\mu m^2$, showing the tremendous potential of SiC SPADs as SiC material quality is expected to be further improved. Various characterization results and approaches to further reducing DCR and increasing SPDE will be presented and discussed to show that SiC SPAD with lower DCR and larger optical window is possible even at present when SiC defect density is still many orders of magnitude higher than that in Si.

4. Summary

A SiC SPAD with an optical window size of Φ50μm is fabricated and characterized. A very low dark current of 57.2fA is achieved at 90% V_{BR}. The linear mode gain reaches $>1.4\times10^6$ at –116.8V. A passive quenching mode single photon counting measurement is performed at the wavelength of 280 nm. The SPAD shows the UV-to-visible rejection ratio of 4.3×10^3. The lowest DCR is 22kHz with an SPDE of 5.65%. The highest SPDE is 9.73% at a DCR of 91 kHz. It is expected that DCR can be further reduced with improvements to structure design, processing technology and material quality.

5. References

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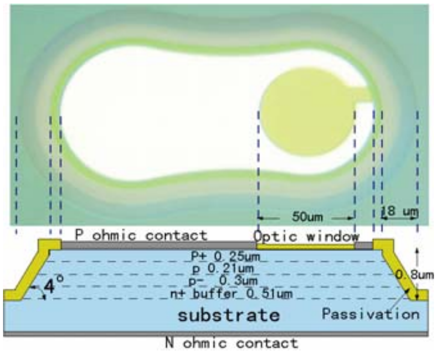

Fig. 1, Top view and cross sectional view of SiC SPAD.

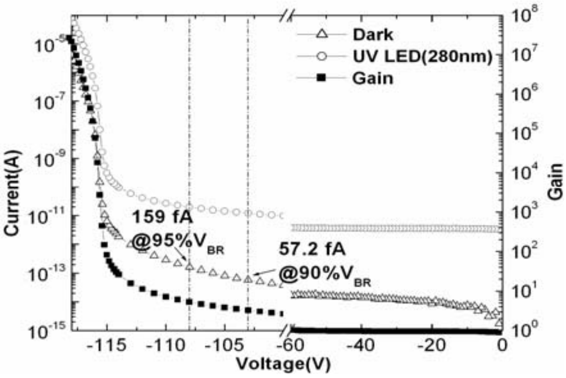

Fig.2: I-V and gain of the SiC SPAD vs. bias.

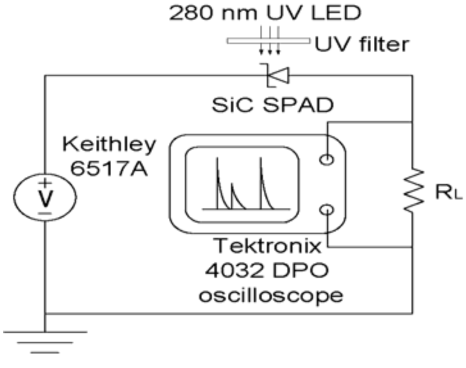

Fig.3, The passive quenching circuit. Tek 4032 DPO oscilloscope is used to sense the signals through a 200Ω load resistor.

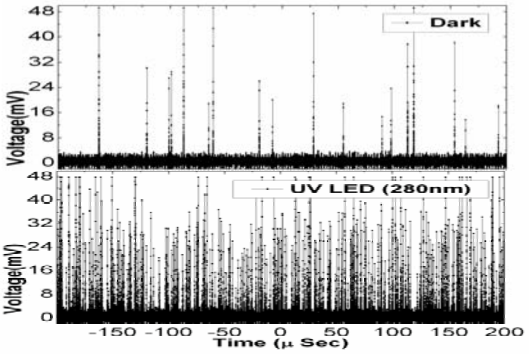

Fig. 4, Dark and photon counting spectra over a very wide, 400μs region for the SPAD biased at 116.8V.