Demonstration of 4H-SiC UV single photon counting avalanche photodiode

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The first 4H-SiC UV single photon counting avalanche photodiode has been designed, fabricated and characterised. Spectral quantum efficiency from 250 to 370 nm is presented. Single photon counting at room temperature is demonstrated for the first time and counting efficiency is reported.

Introduction: Single photon counting detectors enable the receiver of an optoelectronic system to achieve the ultimate receiver sensitivity, the quantum limit. They are also essential in applications that rely on the quantum nature of the light, such as quantum cryptography and quantum computing. Photomultiplier tubes (PMTs) are commonly used for single photon counting because of its high gain and relatively low dark count rate. Semiconductor silicon and InGaAs/InP single photon avalanche diodes (SPADs) have also been developed and widely used as photon counters with major advantages in size, weight, power and lifetime [1]. The spectral response of these solid-state photodetectors extends from 350 nm to near infrared, but is still poor in the UV range owing to the bandgap limitation. Recent progress in the wide-bandgap semiconductor such as SiC and GaN has resulted in the fabrication of UV detectors with high quantum efficiency and low leakage current such as the SiC avalanche photodiodes with extremely high gain ($\sim 10^6$) and low dark current [2]. In this Letter, we present the demonstration of the first SiC SPAD.

Device design and fabrication: The 4H-SiC wafer has a highly doped 0.15 µm $p+$ epilayer, a 0.2 µm p epilayer, and a 4 µm n epilayer on an $n+$ substrate. A two-step multiple junction termination extension (MJTE) is formed by inductance coupled plasma (ICP) dry etching [3]. The size of the devices is 160 × 160 µm. A thermal oxidation layer is grown on top of the wafer at 1050°C for 3 h as the passivation layer, which is then covered by a PECVD oxidation layer and a Si_3N_4 layer. An optical window of 74 × 34 µm is opened by ICP dry etching and HF wet etching. The p-type ohmic contact (Ti) is formed by sputtering and annealed in forming gas. The n-type ohmic contact metal (Ni) on the substrate side is annealed simultaneously with p-contact metal. Au is sputtered as the final overlay metals. The structure of the SiC SPAD is shown in Fig. 1.

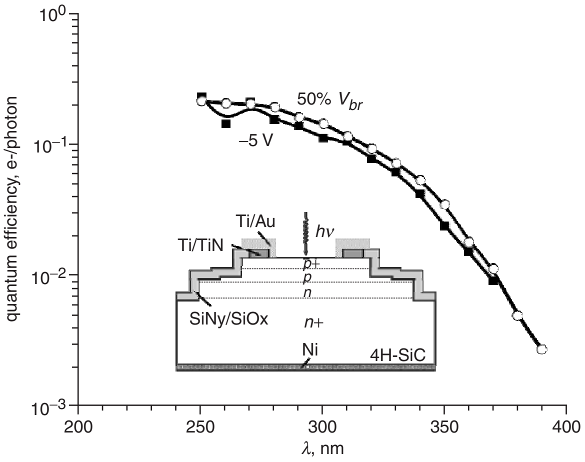

Fig. 1 *Quantum efficiency spectra of 160 × 160 µm 4H-SiC SPAD at different biases*

Spectral quantum efficiency (QE): The breakdown voltage V_{br} is around −78 V. The QE has been measured and calculated from 250 to 370 nm at −5 V and 50% of V_{br} as shown in Fig. 1. The peak QE is between 270 to 280 nm, which is about 20% at 50% V_{br}. The peak of the response curve is located at 270 nm. The QE decreases slowly as wavelength increases for wavelengths longer than 280 nm because of the indirect bandgap of 4H-SiC. At 385 nm, the band edge of 4H-SiC, the photo current is lower than the system detection limit. For wavelengths shorter than 270 nm, the QE decreases as the wavelength decreases, partially due to the surface recombination.

Single photon measurement: A passive quenching circuit is used for single photon measurement as shown in Fig. 2. The UV source is a commercially available UV LED peaked at 353 nm, with an emission spectrum ranging from 338 to 400 nm. The device under test is biased at a particular voltage around the avalanche breakdown region as shown in the I-V curve in Fig. 2 and the load resistance is 200 Ω. 4H-SiC has a 35 µm penetration depth around 350 nm. Thus, most of the photons are absorbed in the thick n epilayer. Part of the photon-generated holes in this region might diffuse into the depletion region and experience avalanche multiplication. Each multiplied hole will generate a current pulse, which leads to a voltage drop on the load resistance. When the multiplication gain is very high, the voltage drop on the load resistance due to the pulse current substantially reduces the bias voltage on the APD under test and quenches the avalanche multiplication until the pulse is over. In this experiment, the voltage fluctuation on the load resistance is monitored at room temperature by a 500 MHz Tektronics TDS 3054B oscilloscope. Fig. 3 shows the single photon counting spectra measured in the dark and under LED illumination. At a bias of −77.9 V (Fig. 3*a*), the dark count rate is less than 500 kHz, but the signal pulse is too weak to be separated from the noise at a threshold of 3 mV. By increasing the bias to −78.0 V (Fig. 3*b*), the current gain is significantly improved and the signal pulse height increases to about 8 mV. The dark count rate at −78.0 V is still low and equal to 650 kHz.

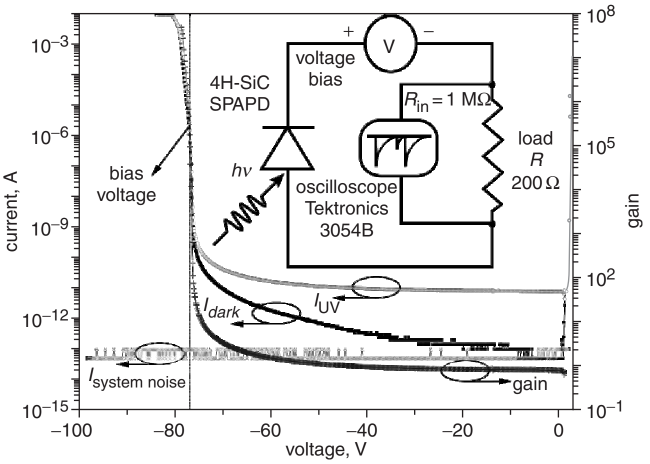

Fig. 2 *Dark and UV-illuminated I-V characteristics and photocurrent gain of 160 × 160 µm 4H-SiC SPAD*

Inset: Photon counting setup

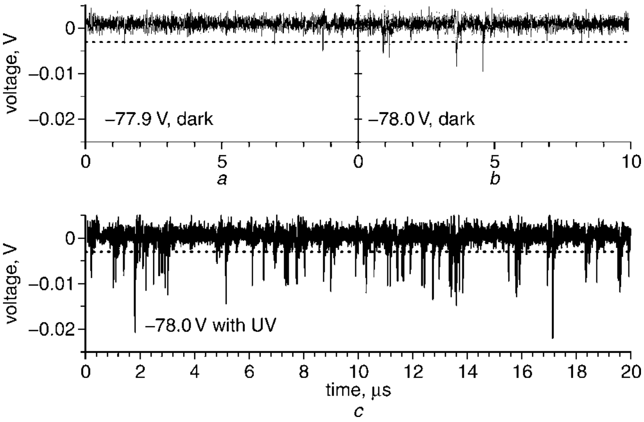

Fig. 3 *Photon counting spectra for 160 × 160 µm 4H-SiC SPAD*

a −77.9 V (dark)
b −78.0 V (dark)
c −78.0 V (LED UV light)

In the photon counting test, the device is biased at −78.0 V. The LED UV flux incident onto the 74 × 34 µm optical window is 1.9×10^{-10} W, corresponding to a flux of 280 photons/µs. With a spectrum average QE of 1.6% at 50% V_{br}, the number (n_p) of photons absorbed per µs by the SPAD that contribute to the creation of electron-hole pairs leading to the measured photocurrent is equal to 6. The n_p carriers might be multiplied and finally counted as signal pulses. Fig. 3*c* shows that the photon count rate is about 4.5 MHz (89 signal pulses in 20 µs), which means the probability for n_p to be counted is 75% (photon count rate 4.5 MHz divided by six absorbed photons/µs). The corresponding average photon counting efficiency is therefore 1.2%. At the peak wavelength of 353 nm, the photon counting efficiency is estimated to be 2.6% (3.5% QE times 75% counting probability). Photon counting measurement for UV light with wavelengths in the solar blind range, namely 240 to 280 nm, has also been tried by using a Xe-lamp as the light source. But due to the fluctuation of the noise from the Xe power supply, it is very difficult to estimate the photon counting rate. Further experiments are in progress for photon counting in this important wavelength range. As the quantum efficiency is about 20% between 260 and 280 nm (Fig. 1), the photon counting efficiency can be expected to be ~15% in the solar blind range. It should be mentioned that the quantum efficiency of SiC avalanche photodiodes can be substantially improved by using a separate absorption and multiplication (SAM) structure and a photon counting efficiency greater than 40% should be achievable.

The rise time t_r of the signal pulse is estimated as 1.3 ns after considering the time constant of the 500 MHz Tektronix oscilloscope. The gain G_{SiC} of the device at −78.0 V is 0.26×10^6 (Fig. 2). The load resistor is 200 Ω. Thus, the pulse height V_{pulse} is estimated as 8 mV, by using:

$$V_{pulse} = q\, G_{SiC}\, R / t_r$$

where q is the elementary charge of one electron. V_{pulse} agrees very well with the average pulse height 8 mV estimated from Fig. 3*c*.

By taking the area of the device into consideration, the demonstrated SiC SPAD dark count rate in passive mode is more than one order of magnitude lower than those of InP/InGaAsP SPADs [4] and GaN SPADs in Geiger mode [5]. Work is under way to evaluate the SiC SPAD in Geiger mode which is expected to show a lower dark count rate compared to that of passive mode.

Conclusion: 4H-SiC APD single photon counting has been demonstrated at room temperature for the first time. At −78.0 V, the probability of photons being counted is 75%. The corresponding photon counting efficiency is determined to be 2.6% at 353 nm. The dark count rate at room temperature is 650 kHz, while the photon count rate is 4.5 MHz. The dark count rate is more than an order of magnitude lower than that of InP/InGaAsP and GaN SPADs operating in Geiger mode.

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