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A hybrid photon detector based on SiC Schottky diode

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Abstract: A new type of hybrid photon detector (HPD) based on SiC Schottky diode, with good radiation resistance and large sensitive area, has been constructed for either steady or pulsed light illumination. A series of experiments were carried out to examine its performance. As a result, the prototype SiC-HPD obtained a gain varying from 0 to 418, when the acceleration high voltage was up to 10 kV. In addition, the prototype SiC-HPD showed a nanoseconds time response with leading edge of 3.5 ns (FWHM ~ 16.6 ns) and a maximum output current around 0.65 A under long pulse irradiation. The results indicate that the SiC-HPD is a very promising detector with high gain, fast-time-response and high pulse linearity current for the radiation-field measurements.

Keywords: Electron multipliers (vacuum); Hybrid detectors; Photoemission

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Contents

1 Introduction

Hybrid photon detector (HPD) [1, 2] is a photon sensitive vacuum tube, employing a semiconductor detector (traditionally a silicon-based device) to collect photoelectrons generated from the photocathode. The photoelectron is accelerated by a high voltage electric field and will induce abundant of electron-hole pairs in the semiconductor detector, which offers the HPD hundreds-times electric charge multiplication. Compared with photomultiplier tubes (PMTs), the HPD is outstanding in resolving single and multiple photoelectrons counting peaks [3]. HPD mounted with a solid-state pixel sensor has been used as the Ring Imaging Cherenkov (RICH) detector for the LHCb experiments [4, 5]. However, the application of HPD is typically used in weak light source measurements, and rarely applied in light sources with high intensity as well as the flash light measurements. Furthermore, the application of Si-HPD in harsh radiation environment is also restricted for the deterioration of the silicon-based device.

To address the deficiency in radiation hardness of silicon-based devices, a prototype SiC-HPD based on SiC Schottky diode has been constructed. SiC is a wide band gap semiconductor material, and shows high resistance to elevated temperatures and endurance to radiation induced damage [6, 7]. Besides, SiC Schottky and PiN diode detectors have been successfully applied in the detection of various radiation particles, such as neutron and alpha [8–10], which can be fabricated to the scale of several centimeters [11]. In the SiC-HPD, the SiC Schottky diode was embedded to detect the energetic electrons with the energy about several keV. In this paper, the structure of the new SiC-HPD prototype is presented, and the performance of the detector under both current and pulsed light source illumination has been investigated experimentally.

2 Experimental

The structure of the SiC-HPD prototype is shown in figure 1, which consists of a SiC Schottky diode, a multialkali photocathode and electron focusing structure (three focusing electrodes) enclosed in the vacuum tube. The SiC Schottky diode is mounted at the center of the ceramic base entrance window, with a diameter of $\Phi 18\,\text{mm}$. The interval between the diode and the facing the quartz entrance window. The photocathode is deposited on the inside surface of the photocathode is about 30 mm. To keep this HPD functioning properly, negative high voltage has to be applied on the photocathode and the focusing electrodes, and the SiC Schottky diode should work in reverse bias condition.

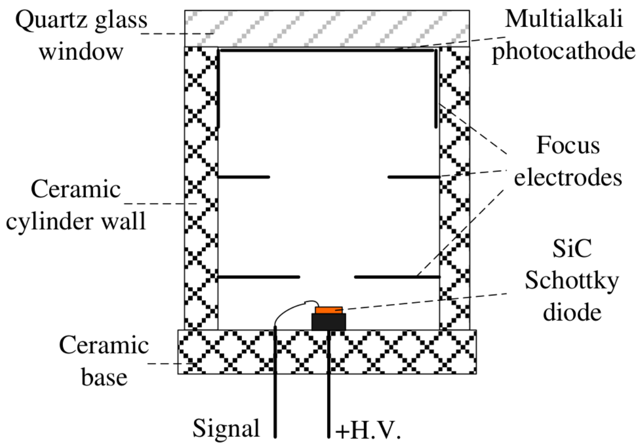

Figure 1. Cross-sectional view of the prototype SiC-HPD.

The schematic diagram of the employed SiC Schottky diode is shown in figure 2. The sensitive region of the SiC Schottky diode is a lightly N-doped ($< 10^{14}\,\mathrm{cm}^{-3}$) epitaxial 4H-SiC layer grown on a commercial 4H-SiC N+ conducting substrate wafer by chemical vapor deposition (CVD). The thickness of the epitaxial layer and the substrate wafer is 35 µm and 350 µm, respectively. The front electrodes are the Schottky contact made with 100-nm-thickness nickel and covered with Au with a thickness of 100 nm. The back electrodes are ohmic contact, made with Ni/Au (100 nm/3 µm). The sensitive area of the diode is $4.8\,\mathrm{mm} \times 4.8\,\mathrm{mm}$. The marginal area with a width of 0.1 mm in width and 1 µm in thickness is reserved for the guarding ring, formed by ion implantation process.

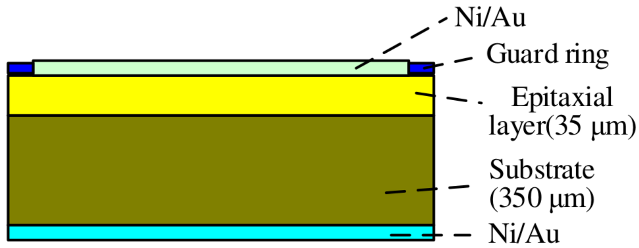

Figure 2. Schematic diagram of the 4H-SiC Schottky diode.

The experiments were conducted with the illumination of steady and pulsed light sources respectively, namely the DC mode and the pulsed mode. In the DC mode, the SiC-HPD was illuminated by a stationary white light source (Yokogawa, AQ4305), and the output current from the detector was recorded by a sensitive current meter (Keithley 6517A). While in the pulsed mode, a fast nitrogen molecular laser source (LTB Laser technik, MNL800, 337 nm, 800 ps) and a slow Xenon flash lamp (Hamamatsu) with time duration at the scale of microseconds were employed, and the pulse signals of the SiC-HPD were recorded with an oscilloscope (Tektronix 4104, 1 GHz).

3 Results and discussion

3.1 DC mode

As shown in figure 3, the intrinsic I-V characteristic of the SiC Schottky diode was tested. The forward bias I-V curve (in figure 3(a)) shows good rectifying characteristic. The ideality factor of the Schottky diode fitted with the Bethe equation is 1.17, which indicates the current is dominated by thermionic current. The leaking current of the SiC Schottky diode increases monotonously with the reverse bias voltage (V_{SiC}), as shown in figure 3(b). In radiation detections, the SiC Schottky diode has to work in reverse bias condition. To avoid the degeneration of the diode, V_{SiC} in real working condition is kept below 150 V, and thus the corresponding leaking current is no more than 1 nA.

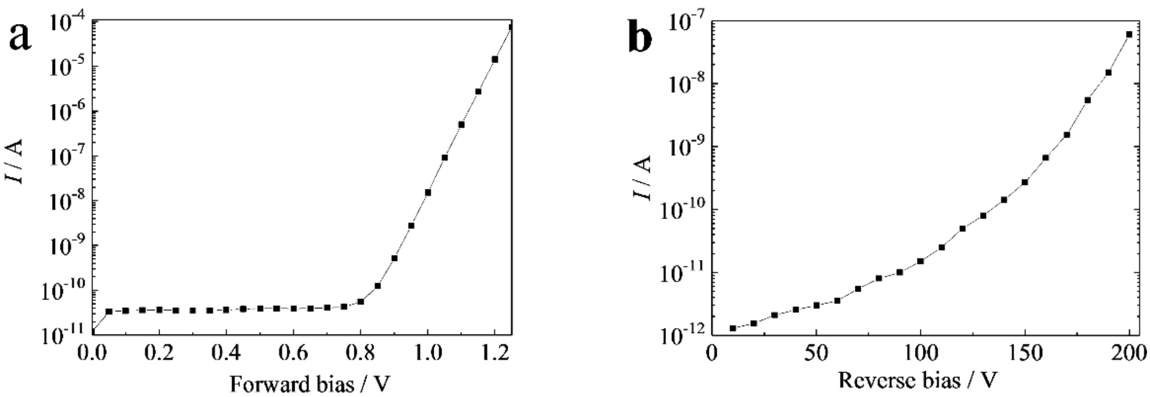

Figure 3. I-V characteristics of the SiC Schottky diode under forward (a) and reverse (b) bias.

The response of the SiC-HPD to light illumination can be expressed as:

$$I = \eta \cdot M \cdot \varphi \cdot e \tag{3.1}$$

where η is the quantum efficiency of the photocathode and the spectral response of the photocathode is shown in figure 4. φ stands for the intensity of light, e is the unit charge, and M represents the multiplication coefficient of electric charge. According to the working process of the SiC-HPD, M can be expressed as:

$$M = \frac{V_{\text{cathode}}e - \Delta E}{\varepsilon} \tag{3.2}$$

where ΔE is the energy lost in the electrode, V_{cathode} is the high voltage applied on the cathode, and ε is the average ionization energy to generate a pair of electron-hole pair in SiC device (about 7.8 eV [10]). It should be pointed out that the contribution of back scattering electrons is not taken into account in Formula 2, though there is a certain probability that high-speed electrons can escape from the surface when colliding with the material. [12] But the contribution of back scattering electrons is relatively small, thus the actual gain will be slightly lower than that calculated in Formula (3.1). Supposing $V_{\text{cathode}} = -10$ kV, $\Delta E = 6$ keV, M of SiC-HPD according to Formula (3.2) is 512.8.

Since the response of the SiC-HPD to light is affected by either V_{cathode} or V_{SiC}, we measured the dependence of the output current on each of the voltage by keeping the other one unchanged.

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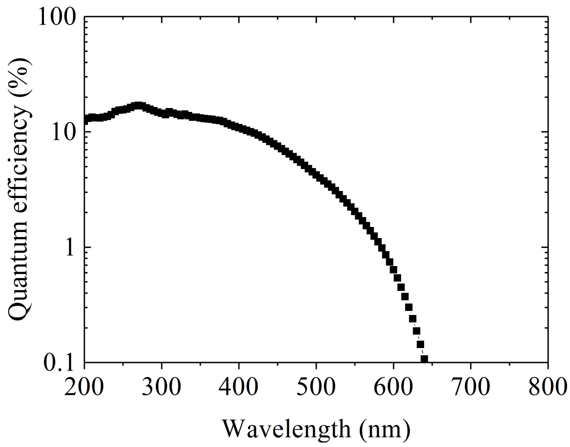

Figure 4. Spectral response of the photocathode.

Figure 5 shows the variance of the output current with V_{cathode} at a given V_{SiC}. According to the curves in figure 5(a), the SiC-HPD is insensitive to light when V_{cathode} is below 6 kV, which indicates that there is a threshold around 6 kV. When V_{cathode} is beneath the threshold, the energy of the photoelectrons obtained from the acceleration electric field is not high enough to penetrate the front electrodes (100 nm nickel and 100 nm Au) of the SiC Schottky diode. While if V_{cathode} is higher than the threshold, photoelectrons can reach the sensitive region of the SiC Schottky diode, and then deposit their residual energy to induce charge carriers in the diode. Therefore, the current increases sharply with V_{cathode} above the threshold. The curves are almost the same for different values of V_{SiC} When the light source is turned off, output current from the SiC-HPD stands for the dark current (I_{d}). As shown in figure 5(b), I_{d} comes from the combination of the leaking current of the SiC Schottky diode and the dark emission of the photocathode.

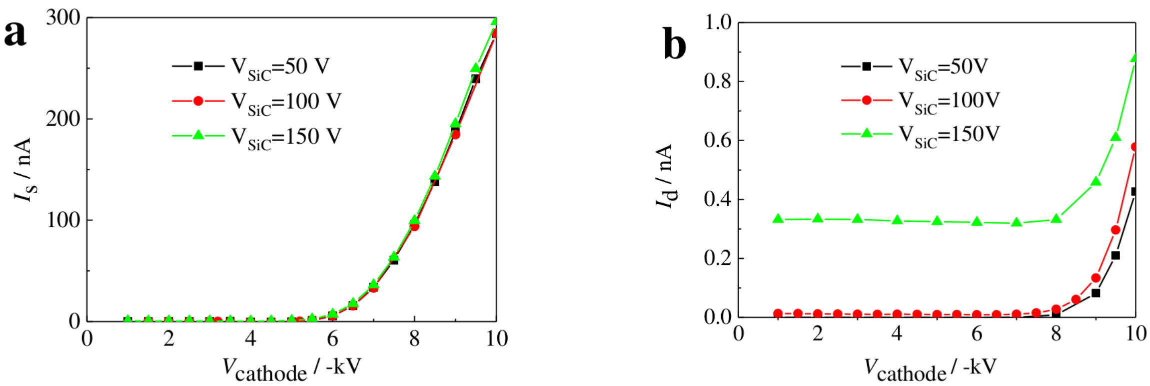

Figure 5. The dependence of signal current (I_{s}) and dark current (I_{d}) on the acceleration high voltage (V_{cathode}) while the light is on (a) and off (b).

Under the same experimental condition, the dependence of the output current on V_{SiC} was also determined while V_{cathode} was fixed at −8 kV and −9 kV. The results are shown in figure 6(a). The output current of SiC-HPD is almost invariant with $V_{\text{SiC},}$ indicating that the response of SiC-HPD is insensitive to the change of the reverse bias voltage of the SiC Schottky diode. This comes from the fact that the average energy of photoelectrons deposited in the sensitive region of the SiC Schottky diode is constant for an individual acceleration high voltage, the average number of electron-hole pairs induced by a photoelectron keeps unchanged. However, the charge collection efficiency of the SiC Schottky diode increases slightly with the reverse bias voltage, [11] leading to the minor growth of the current with $V_{\rm SiC}$. When the light source is turned off, the dark current ($I_{\rm d}$) has an increase dependence on $V_{\rm SiC}$, as shown in figure 6(b).

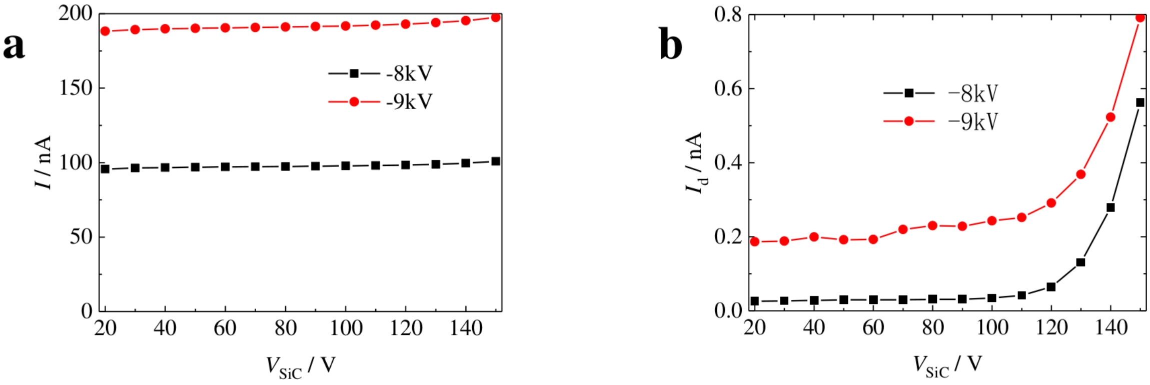

Figure 6. Relationship between the output current and the reverse bias voltage of the SiC Schottky diode ($V_{\rm SiC}$) while the light is on (a) and off (b).

In order to investigate the multiplication of this SiC-HPD prototype, we made a short connection on the surfaces of SiC Schottky diode. In this situation, the SiC Schottky diode served as a typical anode, and the SiC-HPD degenerated to a traditional photo-electron tube. The output current of this detector under illumination reflects the number of photoelectrons collected by the anode without any multiplication, which means $I = \eta \cdot \varphi \cdot e$. Therefore, M of the SiC-HPD equals to the ratio between the current measured under normal and short connection conditions. Figure 7 shows the variation of the output current from SiC-HPD with $V_{\rm cathode}$ while keeping the other experimental conditions unchanged. Since the electron is negatively charged, the output current is negative. The absolute current increases when $V_{\rm cathode}$ is not very high, indicating that the photoelectron collection is incomplete when the $V_{\rm cathode}$ is low. With the increase of the voltage, the photoelectron tends to be fully collected. The curve in figure 8 shows the dependence of M on $V_{\rm cathode}$, which is calculated from figure 5(a) and figure 7.

3.2 Pulsed mode

The pulse response of the SiC-HPD to the sub-nanosecond N_2 laser and the microsecond Xenon lamp are respectively shown in figure 9 and figure 10, where $V_{\rm SiC}$ was fixed at 150 V and $V_{\rm cathode}$ varied from −6 kV to −10 kV. To avoid saturation of the SiC-HPD, the light from the source was attenuated with an optical dimmer before reaching the detector. The SiC-HPD works properly to both short and long pulse light illuminations. The amplitude of the pulse waveform increases with the increase of $V_{\rm cathode}$ while the time characteristic of the waveform remains unchanged. As shown in figure 9, the waveform excited by the laser represents the intrinsic time response of the SiC-HPD, which has a fast leading edge of 3.5 ns and a long exponential decay tail with a constant of 15.2 ns. The long decay tail of the SiC-HPD is due to the relatively large capacitance of the currently

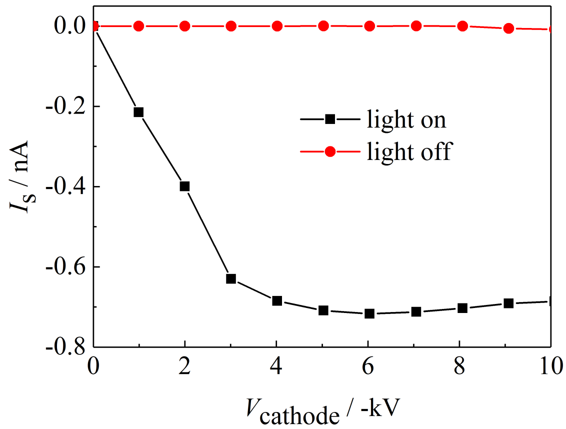

Figure 7. Current measured at different acceleration high voltage while the SiC Schottky diode was short connected.

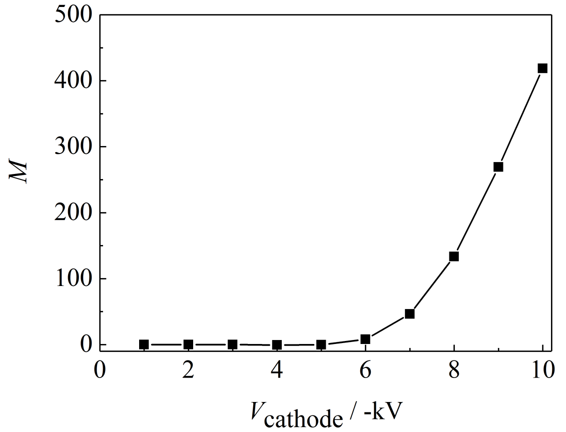

Figure 8. Ratio between the current measured under normal and short connected conditions.

used SiC Schottky diode. The capacitance of the SiC measured is about 0.3 nF (Agilent 4200). In consideration of the 50 Ω resistive load of the oscilloscope, the RC time constant calculated is 15 ns. To reduce the inter-electrode capacitance, it is necessary to increase the thickness of the sensitive layer and reduce the area of the diode. The pulse waveform shown in figure 10 correctly reflects the time characteristic of the pulse Xenon lamp, which has a leading edge of 1.25 μs and a FWHM of 2.85 μs. Besides, we measured the pulse response of the SiC-HPD at different V_{SiC}, when the V_{cathosde} was set to −9 kV. The normalized time response waveforms were shown in figure 11, and the response time was almost independent to the V_{SiC}.

The dependence of the pulse amplitude on V_{cathode} is depicted in figure 12, in which all the points are normalized at −10 kV for each curve. For comparison, the variation of the multiplication coefficient with V_{cathode} derived from figure 8 is drawn as well. All the three curves have a good accordance with each other, indicating that the gain of the SiC-HPD is stable under both current and pulse working conditions.

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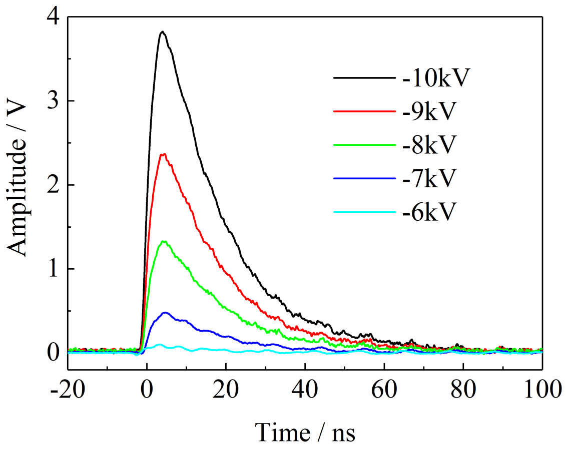

Figure 9. Fast time response of the SiC-HPD to sub-nanosecond N_2 laser pulses.

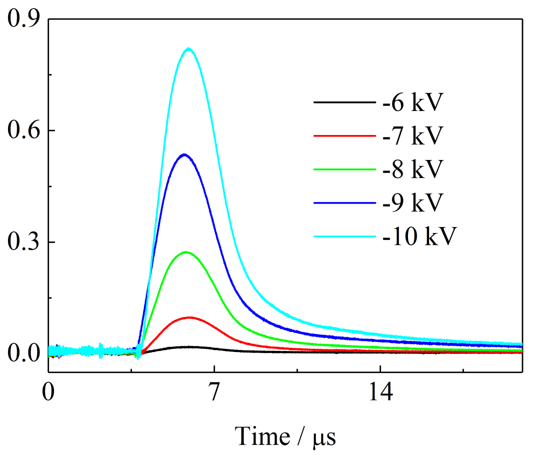

Figure 10. Pulse response of the SiC-HPD to microsecond Xenon lamp.

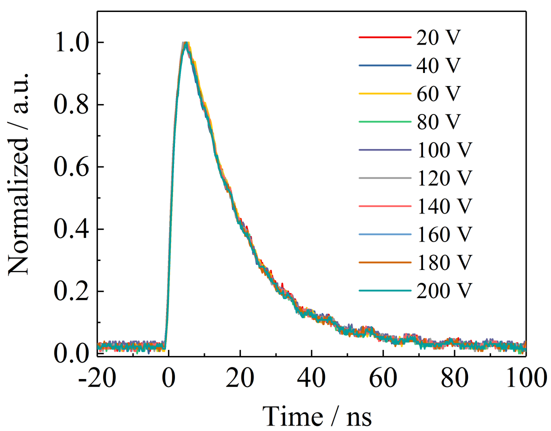

Figure 11. Normalized response of SiC-HPD at different V_{SiC}.

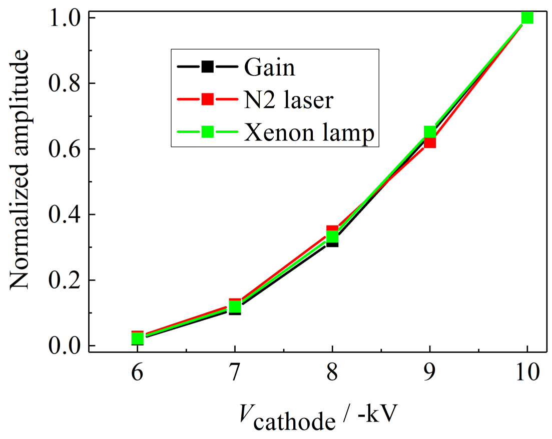

Figure 12. Comparison between the increase of pulse amplitude with acceleration high voltage and the Gain obtained at current mode.

Figure 13 shows the pulse responses of the SiC-HPD to the Xenon lamp at different V_{SiC} when fixing $V_{cathode}$ at −9 kV. From 20 V to 200 V, the pulse amplitude only increases by about 2.5%. This result, on the other hand, verifies that the gain of the SiC-HPD is almost independent of V_{SiC}. By removing the optical dimmer, the saturation pulse response under high intensity illumination was obtained, as shown in figure 14. The recorded pulse waveforms show obvious distortions from the original pulse time property of the Xenon lamp, and temporal profiles change with the V_{SiC}. This phenomenon is mainly attributed to the saturation characteristics of the SiC device. Under strong irradiation, high-density electrons and holes forms plasma, which can shield the electric field, resulting in that the carriers cannot be collected completely. The collection efficiency of the carriers increases with the V_{SiC}. Although the pattern of the profiles distinct from each other at different V_{SiC}, the leading edge of the waveforms lie on the same curve. The leading edge represents the evolutionary process from linear to nonlinear. According to the saturation curves, the maximum amplitude of the signal is about 32.5 V, and the equivalent current is 0.65 A. Using a SiC detector with a larger area is an effective way to increase the maximum linear current of the device.

Furthermore, we studied the pulse response of the electron collection characteristics of the focusing structure, when the SiC Schottky diode was shorten. The $V_{cathode}$ of the HPD was set to −9 kV, and the intensity of photon at the position of HPD increased with the decrease of the distances between the Xenon flash lamp and the HPD. Figure 15 shows an obvious saturation value (∼ −0.12 V) of the response signal in high luminosity conditions (positions 6 & 7), caused by the space-charge effect. This result implies the maximum intensity of the electrons reaching the surface of the SiC diode is limited by the focusing structure.

4 Summary

In this paper, a new type of HPD based on SiC Schottky diode has been developed. Satisfying performance of this SiC-HPD to the illumination of either steady or pulsed light sources was experimentally validated for the first time. The results suggest that the SiC-HPD prototype has a gain varying from 0 to 418, nanoseconds time response with leading edge of 3.5 ns and FWHM of 16.6 ns, and a maximum output current around 0.65 A under long pulse irradiation. The maximum

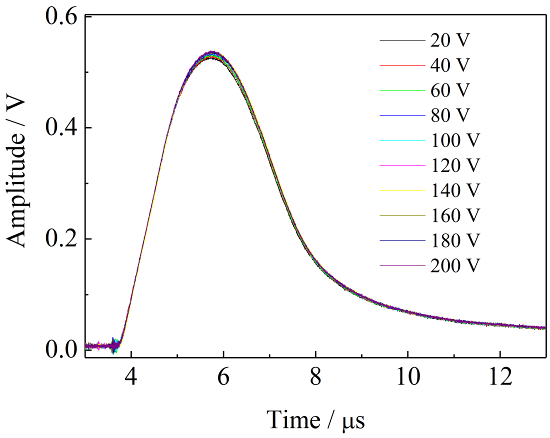

Figure 13. Saturation waveforms to the Xenon lamp with extremely high illumination at different reverse bias voltage of the SiC.

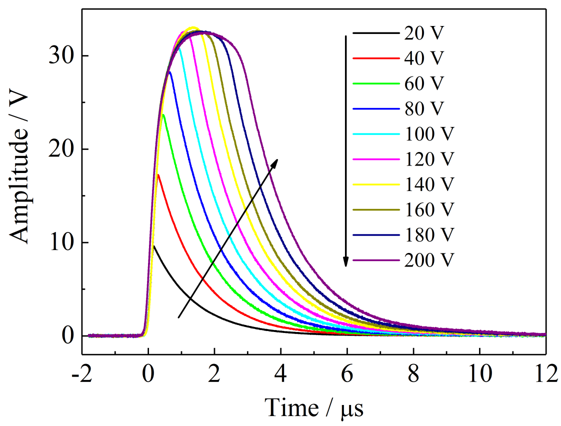

Figure 14. Pulse response to the Xenon lampat different reverse bias voltage of the SiC.

output of the prototype SiC-HPD is dependent on the SiC diode and the focusing structure. And the time response of the SiC-HPD is limited by the SiC Schottky diode for its relatively large capacitance, which can be improved by increasing the thickness of the sensitive region of the diode in the future work. After all, this novel SiC-HPD with various attractive properties, such as large sensitive area, fast time response, relatively high pulse linearity current and hundreds-times electric charge gain, is a very valuable tool and promising candidate for the detection and measurement of pulsed radiation fields.

Acknowledgments

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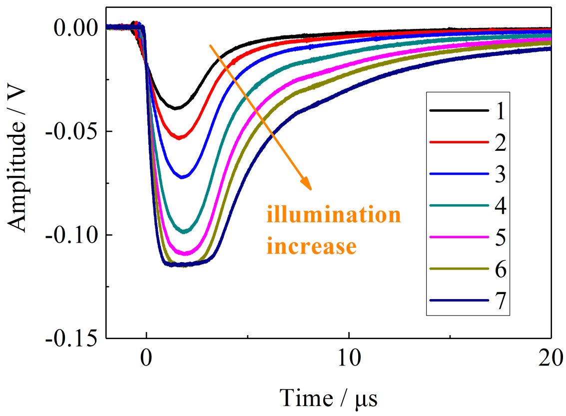

Figure 15. Pulse response characteristic of the HPD when the SiC diode was shorten.

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