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Influence of Gold Nanoparticle Distribution on the Performance of Self-Powered Silicon Carbide Ultraviolet Photodetector

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Abstract. This study presents a systematic investigation into the influence of gold nanoparticles on the performance of a self-powered metal-semiconductor-metal (MSM) 4H-SiC UV photodetector (SiC-UVPD), with a focus on the nonsymmetric contact phenomenon arising from differences in the contact areas of the gold electrode pair under 254 nm UV light exposure. The self-powered SiC-UVPD device exhibited a very good sensitivity of 9.34 x 10^4, great responsivity of 0.30 A/W, and excellent detectivity of 7.0 x 10^{11} cm. $Hz^{1/2}.W^{-1}$ under 254 nm UV light without any external power. In fact, the specific detectivity of the self-powered SiC-UVPD improved by 70 % following the application of Au nanoparticles. Self-powered photodetectors are desirable devices for green energy applications due to their unique advantages such as smaller footprints and wireless operation.

Introduction

Ultraviolet photodetectors (UVPD) attract great attention in optical communications, pharmaceutical and chemical analysis, environmental sensing, flame detection, biomedical electronics, missile detection, and space communications [1]. Photodetectors capable of operating without any external power source can solve the energy requirement along with simplifying and reducing the cost of overall device fabrication. Conventional photodetectors need external power sources to operate, which is not desirable for smart sensor systems and devices. However, self-powered photodetectors can harvest energy from the environment enabling small, portable, cost-effective, and multifunctional devices for future optoelectronic applications [2- 4]. Therefore, improving the performance of these devices has become very crucial for the fabrication of efficient, sustainable, energy and environment friendly devices.

Wide bandgap semiconductors (WBG) such as GaN [5], SiC [6], Ga_2O_3 [7], and AlN [8] are good candidate materials to construct UV photodetectors due to their excellent mechanical, chemical and thermal stability, and radiation resistance. Among these WBGs, 4H-SiC is a very good candidate for constructing UV photodetectors capable of operating at high temperature, high frequency, and high radiation conditions [9] owing to the superior physical properties with a large bandgap energy (3.26 eV), high electron drift velocity (2.2 x 10^7 cm/s), and high thermal conductivity (4.9 W/ cm.K).

One effective technique to enhance the photodetection capabilities of photodetectors is by functionalizing the surface of a semiconductor with metal nanoparticles. These nanoparticles can improve the scattering of incident photons and increase optical absorption around each particle in the active region of the semiconductor, thereby enhancing the overall performance of the photodetector. Furthermore, when metal nanoparticles on the surface of a semiconductor interact with UV light, they can generate localized surface plasmons. These plasmons produce a large number of photoexcited electrons, which can be transferred into the semiconductor, resulting in an increased photocurrent under UV light exposure. Among various metal nanoparticles, gold nanoparticles receive particular attention due to their excellent chemical stability, ease of synthesis, and high density of easily polarizable conduction electrons. These properties enable strong interactions with electromagnetic fields and facilitate the generation of nonlinear optical phenomena [10]. This study presents a systematic investigation into the influence of gold nanoparticles on the performance of a self-powered

MSM 4H-SiC UV photodetector, focusing on the nonsymmetric contact phenomenon arising from differences in the contact areas of the gold electrode pair under 254 nm UV light exposure.

Experimental Details

SiC-UVPD was fabricated via a highly practical and cost-effective fabrication scheme. The photodetector was constructed on a small piece (5 mm x 5 mm) of n-type 4H-SiC wafer with a resistivity of 0.015-0.03 ohm.cm. A physical mask and a sputter coater system were used to deposit nonsymmetrical gold electrodes with a gap spacing of 50 µm and length of 2 mm. The same gold electrode pair was used for all the measurements. The size of the small Au electrode was about half of the large Au electrode. To investigate the influence of gold nanoparticles on the performance of the photodetector, the surface of the fabricated SiC-UVPD was coated with Au for 5 s, 10 s, 15 s, and 20 s deposition times. Following each Au thin film deposition step, the SiC-UVPD was heated at 150°C for five minutes to transform the deposited Au film into nanoparticles. No anti-reflection coating was used in this study. The surface morphology of the fabricated SiC-UVPD and Au-NPs were investigated via scanning electron microscopy. A sourcemeter (Keithley 2634B), which is attached to a probe station and controlled with a Labview program was used to carry out the electrical measurements at room temperature. A UV lamp (UVP-UVLMS 38) with a power density of 1.8 mW/cm^2 and a wavelength of 254 nm was used.

Results and Discussion

Fig. 1 shows a scanning electron microscopy image of the Au nanoparticles on the SiC-UVPD surface and a schematic diagram of the measurement setup of the self-powered SiC-UVPD. The size of the Au nanoparticles ranges from 30 nm to 40 nm for 15 s and 20 s deposition times, respectively.

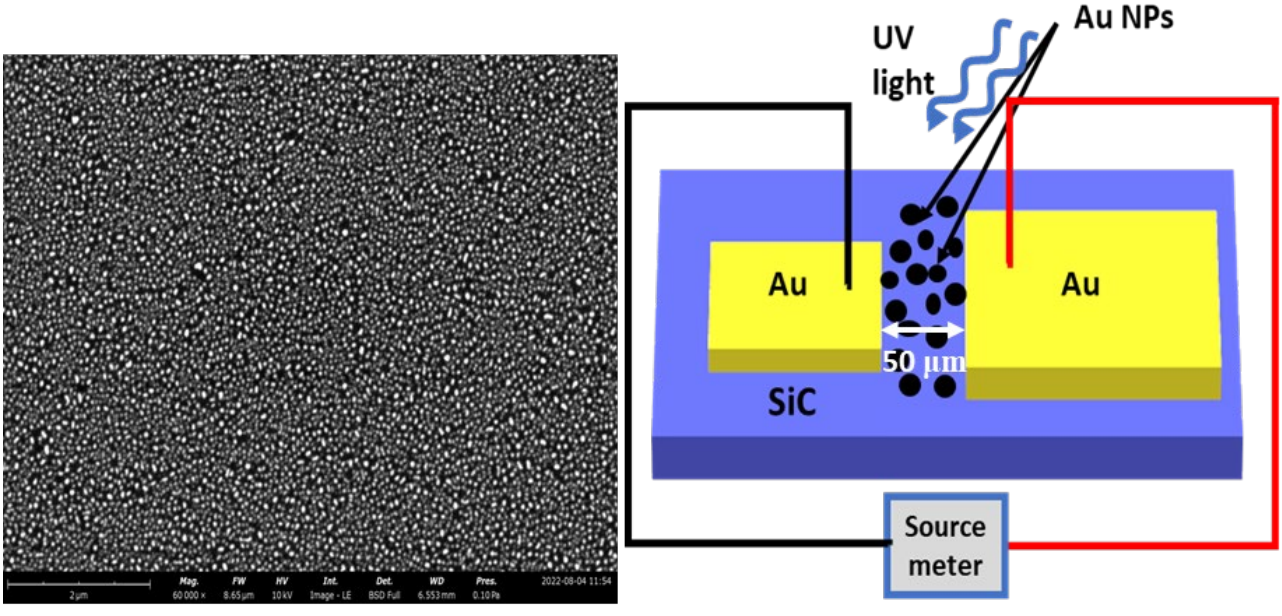

Fig. 1. A scanning electron microscopy image of the Au nanoparticles on the SiC-UVPD (scale bar is 2 µm); and a schematic diagram of the measurement setup of the self-powered SiC-UVPD.

The surface density of gold nanoparticles (Au-NPs in the active area divided by the total active area of the SiC-UVPD) was calculated to be about 3 % and 24 % for the SiC-UVPD-Au15s and SiC-UVPD-Au20s devices, respectively. The size and distribution of the gold nanoparticles after each deposition/heating step were found to be quite uniform. The number and areas of the Au nanoparticles- assuming each nanoparticle to be circular- were calculated. The areal coverage of the Au nanoparticles was then divided by the total gap area of the device.

To evaluate performance characteristics of the SiC-UVPD, current-time (I-t) measurements were performed through 20-s multiple cycles under the UV light at 0 V through a sourcemeter. Fig. 2 displays the I-t plots of the SiC-UVPD following the applications of Au nanoparticles with different surface densities (from 5-s to 20-s Au deposition) at 0 V, revealing strong enhancements in photocurrent. In fact, the I_{ON}/I_{OFF} ratio gradually increases with the increase of Au deposition time reaching to a maximum on/off current ratio of 934 with 15-s Au deposition under 254 nm of UV light. However, a slight decrease on the I_{ON}/I_{OFF} ratio (870) is observed with 20-s Au deposition under 254 nm UV light. Moreover, the SiC-UVPD exhibited a very good sensitivity of 9.34 x 10^4. Furthermore, responsivity, which can be described as the ratio of photocurrent from a photodetector to an incident optical power, is expressed by, $R = (I_{ON} - I_{OFF})/(AxP_{light})$, where A is the active area of the photodetector and P_{light} is the power intensity of incident light. The responsivity of the self-powered SiC-UVPD is 0.18 A/W without any Au NPs, while the responsivity increases to 0.30 A/W with the SiC-UVPD-Au15s under 254 nm UV light.

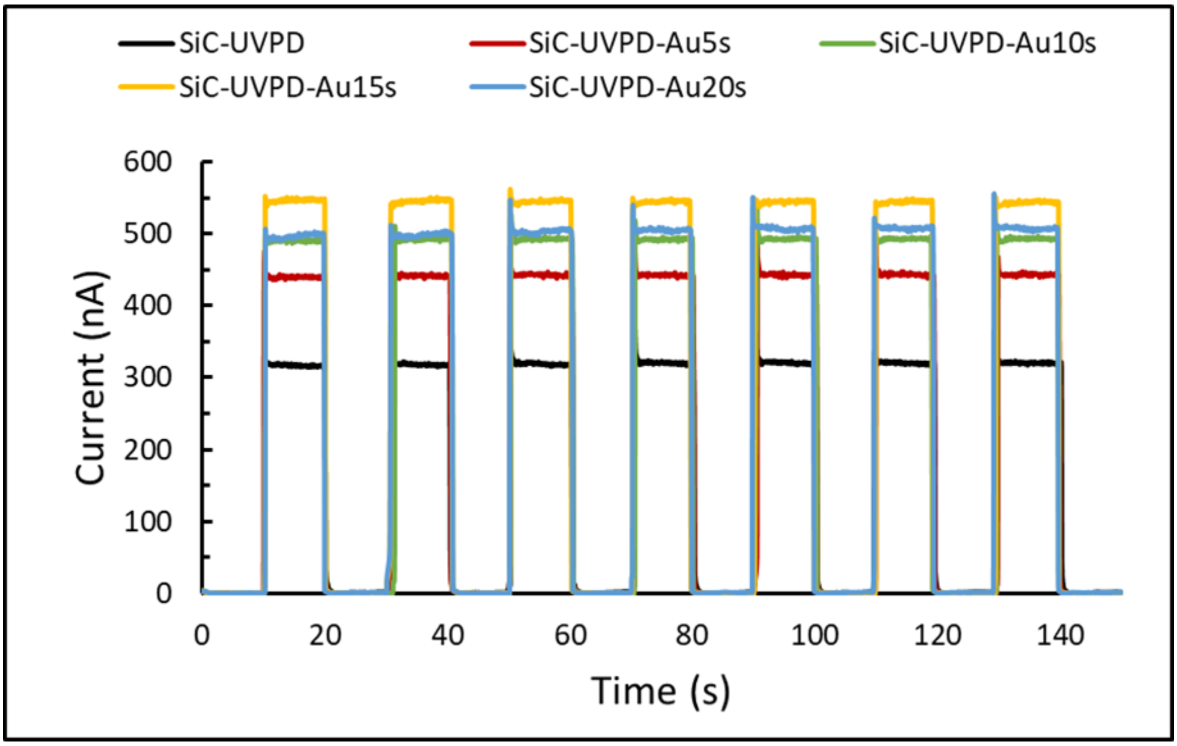

Fig. 2. I-t plots of the SiC-UVPD following the applications of Au nanoparticles with different surface densities (from 5-s to 20-s Au deposition) under 254 nm UV light exposure at 0 V.

Specific detectivity (D*) is described as the ability of a photodetector to detect small optical signals. As the detectivity increases, the capability of the device to sense smaller optical signals increases as well. The specific detectivity is expressed by, $D^* = (R \times A^{1/2}) / (2 \times q \times I_{off})^{1/2}$, where *R* is the responsivity, *A* is the effective exposed area, *q* is the electronic charge, and I_{off} is the dark current. The specific detectivity of the plain SiC-UVPD is 4.12 x 10^{11} cm. $Hz^{1/2}$. W^{-1} under the UV light exposure. Moreover, the detectivity of the self-powered SiC-UVPD improved by 70 % following the application of Au nanoparticles reaching to 7.0 x 10^{11} Jones. Table 1 summarizes some of the performance parameters of the self-powered SiC-UVPD under 254 nm UV light. It is worth noting that a slight decrease in the performance of the SiC-UVPD was observed with 20 s Au deposition under 254 nm UV light. This performance decline can be attributed to the increased surface coverage of the SiC with Au nanoparticles at this deposition duration. A similar trend was reported for a ZnO photodetector coated with Pt nanoparticles, where longer Pt deposition times (50 s) led to a decrease in the device performance [11].

Table 1. A summary of some performance parameters of the self-powered SiC-UVPD including on/off current ratios, sensitivity, responsivity, and specific detectivity under the UV light exposure.

Au Deposition time (s)	On/off current ratio	Sensitivity (%)	Responsivity (A/W)	Detectivity ($cm.Hz^{1/2}.W^{-1}$)
No Au NPs	551.40	5.50 x 10^4	0.18	4.12 x 10^{11}
5	761.57	7.61 x 10^4	0.25	5.70 x 10^{11}
10	845.29	8.44 x 10^4	0.27	6.33 x 10^{11}
15	934.71	9.34 x 10^4	0.30	7.00 x 10^{11}
20	869.74	8.69 x 10^4	0.28	6.51 x 10^{11}

Here, it is important to provide an explanation for the self-powering mechanism of the MSM SiC-UVPD device. The traditional MSM photodetectors with two symmetric back-to-back Schottky contacts on a planar surface require an external power source to generate photocurrent. In fact, MSM devices fabricated with two different electrode materials (one ohmic and one Schottky contact) can operate without any external power. Nevertheless, these MSM devices suffer from poor performance and complex fabrication steps. These drawbacks can be overcome by using nonsymmetric pair of planar electrodes with different contact areas enabling efficient separation of the photogenerated carriers due to a difference in electric field built in each Schottky junction [12]. As a result, the difference in Schottky barrier heights between the two junctions without any applied bias voltage under the UV light exposure leads to a substantial photocurrent from the device. In brief, combined with the practical and cost-effective fabrication, the self-powered SiC-UVPD can lead the path towards novel, high performance, emerging sustainable energy, and eco-friendly optoelectronic devices particularly for harsh environments.

Summary

We have successfully demonstrated substantial performance improvement of the self-powered SiC-UVPD device through the applications of Au nanoparticles with varying surface densities. The fabricated SiC-UVPD exhibited a very good sensitivity of 9.34 x 10^4, great responsivity of 0.30 A/W, and excellent detectivity of 7.0 x 10^{11} cm. $Hz^{1/2}.W^{-1}$ under 254 nm UV light without any external power with the Au deposition time of 15 s. However, a slight decrease in the performance of the SiC-UVPD was observed with 20 s Au deposition under 254 nm UV light, which can be attributed to the excessive surface coverage of the SiC surface with Au nanoparticles. In consequence, the presented SiC photodetector could offer great alternatives to produce next-generation self-powered, sustainable, environment-friendly optoelectronic devices capable of operating in harsh environment conditions with minimal maintenance.

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