Ultraviolet and Visible Photodetection using 3C-SiC/Si Hetero-epitaxial Junction

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Abstract. This paper demonstrates the prospect of using a 3C-SiC/Si hetero-structure as an ultraviolet and visible photodetector. The heterojunction has been grown epitaxially on Si-substrate via a Low Pressure Chemical Vapor Deposition technique at 1000 °C. The detector shows a good diode characteristic with a rectification ratio of 1.03×10^3 and a reverse leakage current of 7.2×10^{-6} A at 2V in dark conditions. The responsivity of the device is found to be 5.4×10^{-2} A/W and 3.18×10^{-2} A/W at a reverse bias of 2V under visible (635 nm) and UV (375 nm) illumination, respectively. An energy band diagram is proposed to explain the photosensitivity of the heterostructure.

Keywords: 3C-SiC/Si heterojunction, Responsivity, UV-visible light, Band diagram.

1 Introduction

The photodetectors, which are consisted of only one semiconductor material (such as ZnO, GaN, and Si), absorb the photons which have higher energy than the bandgap of that material. This property limits their applications in wide spectral sensitivity devices, such as- multispectral image sensors and switches [1]-[2]. A number of studies also have reported on wide band photodetectors based on MSM, p-n and p-i-n junction, and metal schottky structure [3]-[4].

Recently, heterojunction based ultraviolet (UV)-visible photodetectors using different materials, for instance, n-ZnO/p-Si [4], ZnO-CdS [1], Cu₂O/ZnO [5], and a-SiC/a-Si [6], have drawn considerable attention. In heterostructure devices, the top wide band semiconductor layer works as a window for low energy photons, which will be then absorbed in the bottom low band gap material.

In addition, Silicon carbide (SiC) is one of the most promising wide bandgap materials due to its excellent chemical stability, as well as its mechanical and electrical properties [7]-[9]. Among 200 polytypes of SiC, only 3C-SiC can be grown epitaxially on a large Si-wafer at around 1000 °C. As a result, the cost of the wafer reduces

significantly [10]. Hence, the 3C-SiC on Si structure has been used for a number of N/MEMS applications, for instance, temperature sensors [11]-[12], piezoresistive sensors [13]-[15], and pressure sensors [16]-[17].

However, due to different thermal expansion coefficients and the lattice mismatch between 3C-SiC and Si, the grown 3C-SiC/Si heterojunction experiences crystal defects and film stress at the interface [18]-[19]. The stacking faults, as well as film quality, can be improved by carbonizing the activated silicon surface before the growth of 3C-SiC [20]-[21]. A number of studies have reported that, despite the presence of crystal defects at the interface, 3C-SiC/Si heterojunction shows excellent diode characteristics and stable electrical behavior [22]-[24]. Most of the SiC based photodetectors focus on detecting the UV light [25]-[26]. Therefore, in this study, we investigate the potentiality of detecting both ultraviolet and visible photons in the same 3C-SiC/Si heterostructure.

2 Device Fabrication and Experimental details

The 3C-SiC film is grown epitaxially on a Si (100) substrate using the LPCVD technique at 1000 °C. Prior to the epitaxial growth process, the Si-substrate was carbonized to ensure a void free Si under the SiC layer. After that, an Alternative Supply Epitaxy method is used to grow 3C-SiC of desired thickness by using silane and propylene as precursors [27]-[28]. The 3C-SiC film is grown to a thickness of approximately 400 nm with a carrier concentration of 10^{16} - 10^{17} cm⁻³.

Fig. 1. (a) A schematic and (b) cross-section diagram of the proposed heterostructure; (c) the fabricated 3C-SiC/Si heterostructure.

In order to create isolated 3C-SiC/Si heterojunctions, the 3C-SiC film is patterned by conventional lithography processes and then etched using plasma etching in a LAM 480 system. Following this, a 100 nm oxide layer is deposited on the film utiliz-

ing a Hitech LPCVD furnace. Consequently, more than 90% of the oxide area is etched from the isolated 3C-SiC top surface and then an n-type highly doped 3C-SiC layer is selectively deposited to make top contact. To form the back contact, the 3C-SiC from the back surface is removed by inductively coupled plasma etching and then Al is sputtered as a back contact. The details of the device fabrication steps can be found elsewhere [29]. A schematic and a cross-sectional diagram of the proposed heterostructure are shown in Fig. 1(a) and (b), respectively. Fig. 1(c) represents a microscopic image of the fabricated devices with different sizes. The current-voltage characteristics of the heterostructure are measured by an Agilent U2722A source measuring unit. A 635 nm and a 375 nm (THORLAB) laser are employed for the photocurrent measurements.

3 Results and Discussion

The I-V characteristics of the n-3C-SiC/p-Si heterojunction in dark conditions and under UV-visible illumination are exhibited in Fig. 2. As observed the heterojunction shows a good rectifying behavior with a rectification ratio (I_F/I_R) of 1.03×10^3 at forward/reverse biases of 2V.

Fig. 2. Current-voltage characteristics of the 3C-SiC/Si heterojunction in dark conditions and under UV (375 nm) and visible (635 nm) light. (Inset shows the zoom-in-view of the IV characteristic in reverse bias conditions).

The I-V characteristic in dark conditions can be modelled by the standard diode equation [30].

$$J = J_0 \left(\exp\left(\frac{qV_{app}}{nkT}\right) - 1 \right) \quad (1)$$

where, J_0 is the reverse saturation current density, q is the electric charge, V_{app} is the applied voltage, n is the diode ideality factor, k is the Boltzman constant and T is the temperature. The ideality factor of the forward bias current is found to be 1.25, which indicates that the forward current dominates by a diffusion mechanism, but also it consists of a small portion of generation-recombination components. The generation-recombination may result from the SiC/Si interface defects.

The photo I-V characteristics are measured under UV-visible illumination at different intensities as shown in Fig. 2. As observed, the influence of both visible (635 nm) and UV (375 nm) light in forward bias current is almost insignificant. However, the current is affected significantly in reverse bias conditions. For instance, the photo current in reverse bias condition (2 V), at an illumination of 2 W/cm², increases by about 69 times as compared to that in forward bias at -2 V. Therefore, the photodetector is connected in reverse bias to measure the photo-sensitivity. The diode equation in optical environments can be written as-

$$I = I_0 \left(\exp\left(\frac{qV_{app}}{nkT}\right) - 1 \right) + I_{op} \quad (2)$$

where, I_{op} is the optical generation current.

Fig. 3. Photocurrent of the heterostructure as a function of light intensity at a bias voltage of 2V.

The intensity dependent photocurrents ($I_{ph}=I_{photo}-I_{dark}$) under both UV and visible illumination are shown in Fig. 3. The photocurrent increases significantly under visible illumination compared to that in UV light. For example, the photocurrent in visible light is about 5 times higher than that in UV light at an illumination of 0.5 W/cm^2 and a reverse bias of 2V.

The mechanism behind the observed photocurrent characteristics at different light conditions can be explained on the basis of the energy band diagram (Fig. 4). The band offsets are obtained from [31]. The band diagram of the heterostructure in dark conditions at a reverse bias of 2V is shown in Fig. 4(a). The width of the depletion region in Si will be greater than that in 3C-SiC because of the lower ratio of the hole concentration in p-Si to the electron concentration in the n-3C-SiC side. As observed, the electrons tunnel from the valance band of Si to the trap states and are followed by a thermionic emission to the conduction band of SiC [32], resulting a small current flow in dark environments at reverse bias conditions.

Fig. 4. Electron-hole pair generation and recombination at reverse bias in (a) dark condition, and under (b) visible light (635 nm) and (c) UV light (375 nm).

The photocurrent behavior under visible (635 nm) illumination can be explained by Fig. 4(b), where the light incidence comes from the top 3C-SiC side. Due to the large bandgap of 3C-SiC (2.38 eV), the visible light transmits through the 3C-SiC layer and primarily absorbs in the Si layer, resulting in the photogeneration process of electron-

hole pairs. In reverse bias conditions, the generated holes and electrons move towards the negative and positive terminal, respectively. As there is no barrier under the reverse bias conditions, the photogenerated carriers can easily move towards the opposite potential terminals and hence, the photocurrent increases significantly under visible illumination.

On the other hand, under UV (375 nm) light, the photons mainly absorb in 3C-SiC and some photons will reach the p-Si layer due to the thin (400 nm) 3C-SiC layer. As the incident photon energy (3.32 eV) is much higher than the bandgap of Si (1.12 eV), under UV illumination the photoconversion efficiency of Si is very low and extra photon energies will be lost as heat within the device [30],[33]. However, the photo-generated electron and hole in 3C-SiC will move towards the positive and negative bias, respectively. As a result of a low carrier generation under UV illumination, a higher photocurrent under visible illumination is observed than that in UV light.

Fig. 5. Derived the photon responsivity under UV and visible illuminations relative to the excitation intensity.

The responsivity, as a function of intensity, of the heterostructure as shown in Fig. 5 can be defined as [34]-

$$\mathcal{R} = \frac{I_{ph}}{P_i} = \frac{I_{ph}}{I_i \times A} \quad (3)$$

where, I_{ph} is the photocurrent, I_i is the illumination intensity, and A is the device area. The heterostructure shows a peak responsivity of 5.4×10^{-2} A/W and 3.2×10^{-2} A/W

under the illumination of visible (635 nm) and UV (375 nm), respectively, at an intensity of 66 mW/cm^2 with a reverse bias of 2V. As observed, the photoresponse decreases with increasing intensity. This behavior is primarily ascribed to the carrier screening which reduces the internal electric field [35]-[36]. So, the velocity of the photogenerated carrier decreases and hence they recombine before being collected at the external electrical contacts [37].

4 Conclusion

In summary, an n-3C-SiC/p-Si-type heterojunction photodetector has been fabricated using a LPCVD technique and shows a rectification of 1.03×10^3 . In addition, a peak responsivity of $5.4 \times 10^{-3} \text{ A/W}$ and $3.2 \times 10^{-3} \text{ A/W}$ at 2V is observed under visible and UV illumination, respectively. The mechanism behind the different photo-sensitivity under UV and visible illumination are explained via the energy band diagrams. The results indicate the high potentiality using the same structure for detecting both UV and visible light. Further optimization of thickness of the 3C-SiC film and the use of ultralow illumination intensity are expected to improve the performance of the 3C-SiC/Si heterojunction.

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