Photoresponse of a highly-rectifying 3C-SiC/Si heterostructure under UV and visible illuminations

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Abstract—In this study we report the photo-characteristics of an n-3C-SiC/p-Si heterojunction under ultraviolet and visible illuminations. The 3C-SiC thin film has been grown on Si (100) substrate by a Low Pressure Chemical Vapor Deposition (LPCVD) technique at 1000 °C. The as-grown structure shows an excellent rectification ratio (I_F/I_R) of 1.8×10^6 at $\pm 2V$ and a reverse bias current of 5.5×10^{-9} A at 2V in dark conditions. The heterojunction exhibits good sensitivity simultaneously to both UV (375 nm) and visible (637 nm) illuminations. The results indicate that the fabricated structure could be an excellent platform where detection of a wide spectral illumination is vital. The insight of electron-hole pairs generation and carrier transport mechanism at different illumination conditions is explained in detail via an anisotype heterojunction energy band diagram.

Index Terms—3C-SiC/Si heterojunction, rectification ratio, UV-visible illumination, responsivity, energy band diagram.

I. INTRODUCTION

A Photodetector with high sensitivity and reliability over wide-spectral regions is highly essential for many applications such as full color sensors, multispectral image sensors, and switches [1], [2]. The photodetectors, which consists 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. The advancement in technology and device fabrication processes makes it possible to develop heterostructure based multiband photodetectors for detecting both UV-visible light using the appropriate combination of different materials (n-ZnO/p-Si [3], ZnO-CdS [1], and a-SiC/a-Si [4]). In these structures, a large bandgap material is used as a top layer, hence low-energy photons in the visible range pass through the top layer and are absorbed in the bottom narrower band semiconductor material. Therefore, the strategy of using heterostructure enhances the absorption of both UV and visible photons, which leads to increased device sensitivity.

Silicon carbide (SiC) is one of the most favorable wide bandgap semiconductor materials owing to its superior mechanical and electrical properties, as well as high resistance to thermal and chemical stress [5], [6]. Among 200 polytypes of SiC, only 3C polytype can be grown epitaxially on a large Si-substrate at around 1000 °C and hence the cost of the wafer reduces significantly [7], [8]. By taking the advantages of silicon-orientated mature MEMS processing technologies, 3C-SiC on the Si structure has opened a new platform to develop a wide range of better and low cost highly sensitive physical sensors for harsh environments.

Although the best efforts have been made to grow high quality 3C-SiC film on Si-substrate, the grown 3C-SiC/Si heterojunction experiences crystal defects and film stress at the interfaces due to different thermal expansion coefficients and the lattice mismatch between 3C-SiC and Si [9], [10]. The crystal defects, mainly stacking faults, as well as film quality can be improved by carbonizing the active silicon surface before the deposition of 3C-SiC [10], [11]. A number of studies have reported that, despite the presence of crystal defects at the interface, 3C-SiC/Si heterojunction show excellent diode characteristics with a large valance band offset (1.7 eV) between SiC and Si [12]- [14]. As such, the large effective barrier height could be very useful for many applications, such as piezoresistive sensors [6], piezo-Hall devices [15], and biomedical applications [16], where electrical isolation between 3C-SiC and Si is essential.

Silicon carbide based photodetectors are primarily used for UV detection and their peak responsivities are around 260-400 nm [17]- [19]. Since, 3C-SiC has a smaller band gap (2.38 eV) compared to other SiC polytypes, typically 3C-SiC should show better spectral response in the UV/blue spectral region. Therefore, this study investigates the potential of detecting both ultraviolet and visible photons in the same 3C-SiC/Si heterostructure. The rectification ratio of the fabricated heterojunction is found to be 1.8×10^6 , which is one of the best rectification ratio values for 3C-SiC/Si devices in the literature to date, leading to the improvement in dark current and responsivity. In addition, the insight of the carrier transport phenomena in the proposed heterostructure is discussed in detail based on the analysis of the energy band diagram.

II. DEVICE FABRICATION AND SETUP

Employing a Low Pressure Chemical Vapor Deposition (LPCVD) technique, the 3C-SiC (100) film is deposited epitaxially on a Si-substrate (100) at 1000 °C [20], [21]. The 3C-SiC film is grown to a thickness of approximately 300 nm with a carrier concentration of 10^{16} - 10^{17} cm³. The 3C-SiC film is patterned using conventional lithography processes to create isolated 3C-SiC/Si heterojunctions and then etched using plasma etching in a LAM 480 system. Following this, a 100 nm thick oxide layer is deposited on the film utilizing a Hitech LPCVD furnace at 440 °C. The deposited SiO₂ will reduce the perimeter leakage around the mesa structure by passivating the SiC surface. It will also protect the mesa structure exposed 3C-SiC/Si heterojunction area from contaminations and the effects of any further high-temperature processing.

Consequently, more than 90% of the oxide area is etched, using a buffered oxide etch, from the isolated 3C-SiC top

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

surface to form windows for the deposition of heavily doped n-SiC layer (90 nm) to create top contacts. To make the bottom contact, the 3C-SiC from the back surface is removed by inductively coupled plasma etching and then Al is sputtered on the exposed Si as a back contact. The details of the device fabrication steps can be found elsewhere [12]. A schematic and a cross-sectional sketch of the 3C-SiC/Si heterostructure are shown in Figs. 1(a) and (b), respectively. Figure 1(c) shows a microscopic image of the fabricated devices. The current-voltage characteristics of the heterostructure are measured by a Keithley 2450 SourceMeter. A 637 nm (Thorlab) and a 375 nm laser (Nichia) are employed for the photocurrent measurements.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the I-V characteristics of the n-3C-SiC/p-Si heterojunction in dark conditions and under UV-visible illumination. The ratio of forward and reverse current (in dark conditions) at ± 2 V is found to be 1.8×10^6 , indicating the superior rectifying behavior of the structure. The ideality factor of the forward bias current is found to be 1.24, which indicates that the forward current dominates by a diffusion mechanism, but it also consists of a small portion of generation-recombination components. The generation-recombination may result from the SiC/Si interface defects. Figure 2(b) shows the excellent repeatable and stable photoresponse of the heterostructure when the light is turned ON and OFF under both 375 nm and 637 nm illuminations. In addition, the linear increasing trend of the photocurrent (I_{ph}) with illumination intensity indicating that the proposed structure could be used as a self-power photodetector [22]. The device exhibits a relatively fast response and recovery time compared to the reported UV-visible photodetectors [1], [3], [23]. The response time and recovery time are found to be 0.32 s and 0.36 s, respectively, under 375 nm illumination, and 0.35 s and 0.40 s under 637 nm illumination. It is expected that the actual device response time will be even faster, considering the time resolution of the illumination source and the I-V measurement instrument. In addition, as observed, the variation in current density is almost insignificant under forward bias conditions

Fig. 2. (a) Current-voltage characteristics of the 3C-SiC/Si heterojunction in dark conditions and under UV (375 nm) and visible (637 nm) illumination at different intensities, (b) repeatability of the response, (c) response and recovery time, and (d) photocurrent of the heterostructure as a function of light intensity at a reverse bias voltage of 2V.

(Fig. 2(a)). However, the reverse current density varied significantly in reverse bias. For instance, the photocurrent density at a reverse bias (2 V) condition increases about 72 times than that in the forward bias (-2 V) condition (56 mW/cm², 637 nm). Hence, the photodetector is connected in reverse bias conditions to measure the photosensitivity.

Figure 2(d) shows the intensity dependent photocurrents ($I_{ph} = I_{Light} - I_{Dark}$) under both UV and visible illumination. As observed, the I_{ph} increases with the increase of illumination intensity. Because the carrier generation rate, at a fixed wavelength and under steady state conditions, mainly depends on the incident photon flux intensity and hence more carriers will generate at higher intensities [24], [25]. Moreover, the I_{ph} increases significantly under visible light, which is about 5.3 times higher than that in UV light (0.2 W/cm², 2 V). The mechanism behind the photocurrent characteristics at UV and visible light conditions can be qualitatively explained through an energy band diagram analysis, where the band offsets are obtained from [26]. Figure 3(a) shows the energy band diagram of the heterojunction in dark conditions at a reverse bias of 2 V. Due to the lower ratio of hole concentration in p-Si (5×10^{14} cm⁻³) side to the electron concentration in n-3C-SiC side (10^{16} - 10^{17} cm⁻³), the depletion width in Si is greater than that in n-3C-SiC. As observed, the electrons tunnel from the valance band of Si to the trap states at the 3C-SiC/Si interface and are followed by thermionic emission to the conduction band of 3C-SiC, resulting in a small current flow in reverse bias conditions.

Figure 3(b) shows the energy band diagram of the heterostructure under visible (637 nm) illumination, 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 top layer and primarily absorbs in the bottom Si-layer, and generates electron-hole (e-h) pairs in Si. The generated electrons and holes move toward the positive and

Fig. 3. Energy band diagram of the heterostructure and carrier transport mechanism at reverse bias conditions in (a) dark conditions, and under (b) visible light (637 nm) and (c) UV light (375 nm).

negative terminals, respectively, as there is no barrier in reverse bias condition. As a result, the I_{ph} increases significantly under visible light.

On the other hand, under UV (375 nm) illumination, because of the thin (300 nm) 3C-SiC layer, a small portion of the incident photons will absorb in the 3C-SiC (transmittance $\sim 78\%$ at 375 nm) and remaining photons will reach the bottom p-Si layer (Fig. 3(c)). As the incident photon energy (3.32 eV) is much higher than the bandgap of Si (1.12 eV), under UV light the photoconversion efficiency of Si is very low and extra photon energies will be lost as heat within the device [26], [27]. The photogenerated electrons and holes in 3C-SiC will move toward the positive and negative terminal, respectively. However, due to a low e-h pair generation under 375 nm illumination, a lower I_{ph} is observed under 375 nm light than that under 637 nm illumination. A thicker 3C-SiC top layer will absorb more UV photons, and therefore, it is expected that a higher I_{ph} will be generated. This effect will be investigated quantitatively in a future study.

The performance of a photodetector can be examined by its responsivity (R_e) at a particular wavelength, which is defined as [28], $R_e = I_{ph}/P_i = I_{ph}/A \cdot I_i$, where, I_i is the illumination intensity and A is the device area. Figure 4 shows the responsivity of the fabricated heterostructure at different light intensities. The structure shows a peak responsivity of 10.9×10^{-2} A/W and 3.2×10^{-3} A/W under the illumination of 637 nm and 375 nm, respectively (0.5 mW/cm^2 , 2 V). It is also observed that the responsivity decreases with increasing illumination intensities. The observed phenomenon may attribute to the advantage of low reflectance due to scattering at low intensities, endowing the higher photoconversion efficiency at lower intensities than that in higher intensities [29], [30]. The spectral responsivity of the device (at an intensity of approximately 6.6 mW/cm^2) is shown in Fig. 4(b). As observed, the device shows the maximum responsivity

Fig. 4. (a) The responsivity of the 3C-SiC/Si heterostructure under UV and visible illuminations at different excitation intensities and (b) spectral responsivity of the device at an intensity of approximately 6.6 mW/cm^2 .

around the red wavelengths, which can be attributed to the optimum photo-current conversion efficiency of Si near these wavelengths [31], [32].

To investigate the advantages of a highly rectifying 3C-SiC/Si heterojunction, we also fabricate a heterostructure with low rectification ratio (1.03×10^3). The I_{Dark} and R_e of the device are found to be 7.6×10^{-6} A and 5.4×10^{-2} A/W at a reverse bias of 2V (60 mW/cm^2 , 637 nm), respectively. The results indicate that the I_{Dark} and R_e of the highly-rectifying device are about three orders lower and 1.5 times better, respectively, than that of the device with low rectification ratio. The improvements are attributed to the significant reduction of dark current and increase in the internal field across the junction in the highly-rectifying device.

IV. CONCLUSION

In summary, we fabricated an n-3C-SiC/p-Si heterostructure photodetector using a LPCVD technique. The detector shows an excellent rectifying behavior with a rectification ratio of 1.8×10^6 at ± 2 V. A peak responsivity of 10.9×10^{-2} A/W and 3.2×10^{-3} A/W at 2V is observed under visible and UV illumination, respectively. The mechanisms behind the different photo-sensitivity under UV and visible illumination are explained via the energy band diagrams. The results reveal that the fabricated 3C-SiC/Si heterostructure can be used to detect both UV and visible light simultaneously, which could be beneficial for wide spectral sensitivity detectors/devices.

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