3C-SiC/Si heterostructure: an excellent platform for position sensitive detectors based on photovoltaic effect

Abu Riduan Md Foisal,^{*,†} Thanh Nguyen,[†] Toan Dinh,[†] Khoa-Nguyen Tuan,[†]
Philip Tanner,[†] Erik W. Streed,^{‡,¶} and Dzung Viet Dao^{†,§}

[†]*Queensland Micro- and Nanotechnology Centre, Griffith University, QLD, Australia 4222,*

[‡]*Institute for Glycomics, Griffith University, Southport, QLD, Australia 4222,*

[¶]*Centre for Quantum Dynamics, Griffith University, Brisbane, QLD, Australia 4111,*

[§]*School of Engineering and Built Environment, Griffith University, QLD, Australia 4222.*

E-mail: a.mdfoisal@griffith.edu.au

Phone: +61-7-555-27515. Fax: +61-7-555-28065

Abstract

Single crystalline silicon carbide (3C-SiC) on Si-substrate has drawn significant attention in recent years due to its low wafer cost and excellent mechanical, chemical, and optoelectronic properties. However, the applications of the structure have primarily been focused on piezoresistive and pressure sensors, bio-mems, and photonics. Herein, we report another promising application of the heterostructure as a laser spot position sensitive detector based on the lateral photovoltaic effect (LPE) under nonuniform optical illuminations at zero-bias conditions. The LPE shows a linear dependency on spot positions and the sensitivity is found to be as high as 33 mV/mm under an illumination of 2.8 W/cm² (635 nm). The structure also exhibits a linear dependency of LPE

over a large distance (7 mm) between two electrodes, which is crucial for PSDs as the region with a linear dependence of LPE is only usable for PSDs. The LPE at different spot positions and under different illumination conditions have been investigated and explained based on the energy-band analysis. The temperature dependency of the LPE and position sensitivity are also investigated. Furthermore, the 2D-mapping of the lateral photovoltages reveals the potential for utilizing the 3C-SiC/Si heterostructure to detect the laser spot position precisely on a plane.

Keywords

3C-SiC/Si heterostructure, position detector, Lateral photovoltaic effect, energy-band analysis, harsh environments.

Introduction

A considerable amount of research interest has paid for the development of heterostructure based devices as it provides an additional degree of freedom to control and enhance the device functionality and sensitivity by utilizing the distinct electronic, mechanical, and optical properties of two/more dissimilar semiconductor materials.^{1,2} Numerous highly sensitive photodetectors (such as PtSe₂/GaAs,³ β -Ga₂O₃/p-Si,⁴ ReS₂/ReSe₂⁵) and phototransistors (for instance, MoS₂/InGaZnO,⁶ n-Ge/p-Ge_{1-x}Sn_x/n-Ge_{1-x}Sn_x,⁷ GaN/InGaN⁸), and highly efficient solar cells (e.g., WSe₂/MoS₂,⁹ a-Si/c-Si,¹⁰ p-Si/MoS₂¹¹) have been reported based on heterostructures. In addition, heterostructures have also emerged as a suitable structure for position sensitive detectors.¹²⁻¹⁵ Those structures have the advantages of large built-in potential in the heterojunction, which results in increasing the photocarrier separation rate and driving the carriers that migrate toward the external electrical contacts, and wide spectral sensitivity as the devices, usually, combine two/more materials with different optical bandgaps.^{12,16,17}

In general, the position sensitive detectors (PSDs) utilize the lateral photovoltaic effect

(LPE), which results from a non-uniformly illuminated heterostructure.^{13–15} As the lateral photovoltage (LPV) varies significantly with a small displacement of laser spot and shows a linear correlation with the laser spot positions, the PSDs can be used for a diverse range of applications, for instance in robotics, biomedical devices, and rotation monitoring, where controls and measurements with a high precision are vital.^{18,19} The PSDs, usually, operate based on two detection mechanisms: (a) photoconductive principle, where the conductivity changes under illumination, which can be measured under a bias voltage, and (b) photovoltaic principle, under illumination, a voltage is generated, where the generation and separation of photocarriers are primarily controlled by the built-in potential in the heterojunction.²⁰ In photovoltaic mode, a PSD can operate in a self-powered condition, which is vital for a system that is operating with an extensive array of detectors and remote wireless sensor nodes where functioning with power independence is crucial.

The unique electrical, chemical, and physical properties of silicon carbide (SiC) make it suitable for numerous semiconductor device applications including high-temperature sensors,²¹ high power and high-frequency MOSFETs,²² and high voltage diodes.²³ However, small size and high cost of SiC wafers, e.g. 4H-SiC or 6H-SiC wafers, are limiting the potential of producing SiC-based commercially viable devices.²⁴ As a possible solution, the growth of single crystalline cubic-SiC (3C-SiC) has been demonstrated on a large Si-substrate (up to 300 mm) at a growth temperature of 1000 °C, which is well below the melting point of Si.^{25,26} Hence, the cost of the wafer reduces significantly. Furthermore, 3C-SiC/Si structures are more compatible with the mature and advanced Si-based MEMS processing technologies compared to other polytypes.^{24,27} Based on the 3C-SiC/Si heterostructure, numerous devices have already been reported, for instance, strain sensors^{28,29} and pressure sensors,^{30,31} photonics,^{32,33} and solar cells.^{34,35} Furthermore, 3C-SiC/Si structures are also used as substrates for the growth of GaN and AlN, thanks to the low lattice mismatch of 3C-SiC with GaN ($\sim 3\%$) and AlN ($\sim 1\%$), and a number of devices have been fabricated based on these platforms including high power LEDs and high-frequency transistors.^{36–38} However, the po-

tential of utilizing 3C-SiC/Si heterostructures as position sensitive detectors has not been elucidated yet.

In this study, we investigate the position sensitivity of an iso-type p-3C-SiC(100)/p-Si(100) heterostructure based on the lateral photovoltaic effect by illuminating the structure non-uniformly at different positions using a focused laser beam. The as-fabricated structure shows a sensitivity of 33 mV/mm under 635 nm illumination (2.8 W/cm^2) with excellent stability and repeatability at zero-bias conditions. It is expected that the proposed device will show a high position sensitivity over a wide spectral range because the heterostructure consists of two dissimilar semiconductor materials with distinct optical bandgaps (i.e., 2.38 eV (3C-SiC), 1.1 eV (Si)). Furthermore, it is worth to mention that our process deposit 3C-SiC on both sides of the Si-substrate, hence the Si-layer is fully covered and protected by the 3C-SiC layer, which makes the structure as a promising position sensing platform for harsh environments (i.e., high pressure and highly corrosive environments). The experimentally observed position-dependent photoresponse at different illumination conditions and different temperatures has been explained qualitatively by an energy band diagram analysis at zero-bias conditions. In addition, the proposed device consists of a large photoresponse area ($8 \text{ mm} \times 4 \text{ mm}$) and the Al contacts are formed by employing sputtering and conventional photolithography processes, indicating that there is no requirement of any complicated SiC etching process to fabricate the device. Therefore, this study reveals that the 3C-SiC/Si heterostructure could be a simple and cost-effective platform for position sensitive detectors in harsh environments.

Device fabrication and experimental setup

A 300 nm 3C-SiC (100) film was grown epitaxially on Si (100) substrate using an SPT Epiflux SiC epitaxial LPCVD reactor at 1000 °C, employing Silane and Propene as precursors.^{25,26} Trimethylaluminium $[(\text{CH}_3)_3\text{Al}]$ was introduced as a source of *in situ* p-type doping. The

Figure 1: (a) A XRD image of the grown 3C-SiC on Si-substrate, (b) a TEM image of the 3C-SiC/Si heterojunction, (c) a schematic and (d) top view of the proposed 3C-SiC/Si heterostructure.

carrier concentration of the grown SiC film and Si-substrate were found to be $5 \times 10^{18} \text{ cm}^{-3}$ and $5 \times 10^{14} \text{ cm}^{-3}$, respectively, measured by the hot probe technique. A 2θ - θ XRD measurement of the structure shows diffraction peaks at 41.4° and 90.1° , which depicts 3C-SiC (200) and 3C-SiC (400) orientations, respectively, as shown in Figure 1a. The additional peak at 69.2° represents the Si (400) orientation. The results indicate that the 3C-SiC (100) film was grown epitaxially on Si (100)-substrate.

A TEM (Figure 1b) image of the heterointerface depicts that there is no grain boundary in the grown 3C-SiC (100) film and the visible defects, mainly stacking faults, near the heterointerface are a result of the lattice mismatch and thermal mismatch between the 3C-SiC and Si.³⁹ Al electrodes were deposited, employing sputtering and conventional photolithography processes, on the 3C-SiC surface to form a four terminals 3C-SiC/Si heterostructure, as shown in Figure 1c. A brief description of the fabrication process is provided in Figure

Figure 2: Electrical characterization of the 3C-SiC/Si heterojunction: (a) I-V measurements in dark (the inset shows the measurement setup) and (b) stable and repeatable responses in dark conditions and under 635 nm illumination at different intensities (23 mW/cm^2 , 0.9 W/cm^2 , 4.6 W/cm^2) at ($X=+3.5 \text{ mm}$, $Y= 0 \text{ mm}$) position.

S1 (supporting information). The dimensions of the device are $8 \text{ mm} \times 4 \text{ mm}$.

To characterize the LPV and sensitivity of the 3C-SiC/Si PSD, the light was illuminated at a perpendicular direction to the top 3C-SiC side. The optical characterisation was carried out utilizing 405 nm, 521 nm, and 635 nm lasers (Thorlabs). The diameter of the laser beam spot was approximately $370 \text{ }\mu\text{m}$. The laser source was mounted on a 3-axis stage to measure the position sensitivity of the device and the position of the laser spot on the sample was carefully monitored via a computer using a digital microscope (MV30801-WNC, Microvue). Attention was also paid to reduce the influence of any unwanted light, for instance background light, on the device characteristics. To measure the position sensitivity of the heterostructure at different temperatures, the device was mounted on a Linkam stage (HFS600E-PB4), in which temperature can be adjusted precisely by a temperature controller (T95). A thermocouple (METEX, M-6000H) was also attached on the surface of the device to measure the surface temperature of the device. A Keithley 2450 SourceMeter was utilized to measure the electrical characteristics of the 3C-SiC/Si heterostructure. A schematic illustration of the experimental setup is provided in Figure S2 (supporting information).

Figure 3: (a) A schematic of the lateral photovoltage (V_{AB}), which is resulted from the redistribution of photogenerated holes under non-uniform illuminations. Energy band diagram of the 3C-SiC/Si heterostructure when the laser (635 nm) spot position is (b) at electrode A, (c) in the middle, and (d) at electrode B under a fixed illumination intensity.

Results and discussion

The current-voltage characteristics of the as-fabricated 3C-SiC/Si heterostructure is shown in Figure 2a. The linear relationship between I and V indicates that the Al electrodes formed excellent Ohmic contacts on the 3C-SiC surface. To investigate the quality of the 3C-SiC/Si heterojunction, vertical I-V and C-f characteristics of the structure are measured at different temperatures in dark conditions (Figure S3, supporting information). At room temperature, the high (3.7×10^4 at ± 2 V) rectification ratio ($I_R = I_{Forward}/I_{Reverse}$) and the small variation in capacitance with frequency indicate the excellent quality of the heterointerface. However, with increasing temperature, I_R decreases and the variation in capacitance with frequency increases as more trap states near the interface become active and the carrier concentrations increase due to the thermionic emission.²⁵ Figure 3(a) shows a brief schematic of the LPV measurement. The position of zero-point is located in the middle of the top surface (Figure 1d), where the measured V_{AB} and V_{CD} are approximately 0 V.

The measured lateral photovoltage (V_{AB}) is presented in Figure 2(b), when the laser (23 mW/cm², 635 nm) spot position (X, Y) is at (+3.5 mm, 0 mm). As observed, V_{AB} shows stable and repeatable responses at different illumination intensities. Furthermore, an output voltage of 86 mV is observed under an illumination of 0.9 W/cm² (635 nm). In general, when light illuminates on a 3C-SiC/Si heterostructure, the photons (depending on their energies) are absorbed in the 3C-SiC, 3C-SiC/Si junction, and Si-substrate, resulting in the generation of electron-hole ($e_{ph} - h_{ph}$) pairs in the layers. Consequently, the generated $e_{ph} - h_{ph}$ pairs separate due to the large built-in potential at the heterointerface. As depicted in Figure 3a, when the laser spot is at contact A, a large number of $e_{ph} - h_{ph}$ pairs are generated in the neighbourhood of the irradiated region. Thereafter, because of built-in potential, the h_{ph} moves toward the SiC layer and subsequently laterally diffuse over the 3C-SiC-region.^{20,40} The redistribution of h_{ph} creates a hole gradient between the electrodes A and B, resulting in a lateral photovoltage, V_{AB} . Furthermore, Figure 4 exhibits that V_{AB} varies almost linearly with the laser spot position along the line between electrodes A and B, which

can be expressed, in the steady-state condition, as:^{40,41}

$$V_{AB} = \frac{2Kp_0}{\lambda_h} (1 - P^{\frac{\tau p_i}{p_0}}) \exp(-\frac{L}{\lambda_h}) X_L \quad (1)$$

where K is a proportional coefficient, p_0 is the density of photoexcited holes, which can be defined as, $p_0 = (\eta \alpha I \tau / h\nu)$, where η , α , I , τ , and $h\nu$ are the quantum efficiency, absorption coefficient, illumination intensity, carrier lifetime, and incident photon energy, respectively, P is the possibility of h_{ph} to be recombined with the electrons, $2L$ is the distance between two electrodes, X_L is the laser spot position, p_i is the power of incident light, and λ_h is diffusion length of the photoexcited holes. Equation (1) indicates that V_{AB} is linearly proportional to the position of laser spot, which is also agreed with the measured lateral photovoltage (Figure 4).

Figure 4 also reveals that V_{AB} varies from negative potential to positive potential when the laser spot moves from electrode A to B. The underlying physical mechanisms behind the phenomenon can be explained via the energy band analysis (Figures 3b-d). In dark conditions, at thermal equilibrium, the Fermi levels (E_{F-SiC}) of both electrodes will be

Figure 4: Lateral photovoltage, V_{AB} when the laser spot moves from electrode A to B along the X-axis ($Y=0$) under 405 nm, 521 nm, and 635 nm illuminations (23 mW/cm²).

Figure 5: (a) Lateral photovoltage, V_{AB} at position ($X=+3.5$ mm, $Y=0$) and (b) position sensitivity, S_p as function of intensity under the illumination of 405 nm, 521 nm, and 635 nm lasers.

aligned, hence, $V_{AB} = 0$. When the laser spot position is closed to electrode A, the physical picture of the photoresponse is as follows: first, the photogenerated holes (h_{ph}) move towards the top SiC layer whereas the e_{ph} will remain in the Si layer. The h_{ph} will then diffuse laterally towards the A and B electrodes, and the quantity of h_{ph} at each electrode depends on the distance between that electrode and the laser spot position. Hence, electrode A will have more h_{ph} compared to that at electrode B, resulting in the Fermi-level of SiC (E_{F-SiC}) at electrode A moving down towards the valence band, while the E_{F-SiC} will remain almost unchanged at electrode B (Figure 3b). Therefore, the potential energy at electrode A will be lower than that at electrode B and thus the lateral photovoltage, V_{AB} , becomes negative. Likewise, when the laser spot position moves close to electrode B, the potential at B becomes lower compared to electrode A and hence, V_{AB} is positive (Figure 3d). However, if the spot position is at the centre of the two electrodes, because of carrier diffusion symmetry between electrodes A and B, the E_{F-SiC} of both electrodes will be lined up and thus, $V_{AB} \sim 0$, as shown in Figure 3c. Figure 5a shows V_{AB} as a function of intensity, when the laser spot is at ($X= +3.5$ mm, $Y= 0$ mm), under the illumination of different wavelengths. At an intensity of 0.93 W/cm^2 , the V_{AB} is found to be 70 mV, 74 mV, and 86 mV under 405 nm, 521 nm, and

635 nm illuminations, respectively, indicating that the 3C-SiC/Si heterostructure is highly sensitive to the incident light wavelengths. The underlying mechanism can be described as follows.

Under the illumination of 405 nm laser, because of the thin 3C-SiC (300 nm) layer, a small proportion of incident photons will be absorbed in the 3C-SiC layer. For instance, a 300 nm thick 3C-SiC membrane showed a transmittance of about 80% at 405 nm illumination (membrane fabrication and characterization, in details, can be found elsewhere⁴²). Thus, most of the incident photons will be absorbed in the bottom Si-layer. However, the excitation energy (3.06 eV) of the incident laser is much higher than the bandgap of Si (1.1 eV), therefore, the generation of $e_{ph} - h_{ph}$ pairs will be lower and excess incident photon energy will be lost in the form of heat within the device.^{43,44} In contrast, due to the large bandgap (2.38 eV) and thin 3C-SiC layer, under the illumination of a 635 nm laser, the 3C-SiC-layer is almost transparent to the incident photons and hence the photons are passed through the layer and absorbed in the bottom Si-layer. Subsequently, as Si shows higher photoconversion efficiency around the red-NIR (near infrared) region, a large number of $e_{ph} - h_{ph}$ pairs generate in the device under 635 nm illumination.^{45,46} Therefore, more $e_{ph} - h_{ph}$ will be generated in the heterojunction under the illumination of 635 nm (light is at electrode B) and hence the separation of Fermi-energy levels between electrode A and electrode B will be higher compared to that in 521 nm and 405 nm. As a result, the 3C-SiC/Si heterostructure shows a higher lateral photovoltage under 635 nm illumination in comparison with the other mentioned wavelengths (Figure 5a). For these reasons, the 3C-SiC/Si heterostructure showed a higher lateral photovoltage under 635 nm illumination compared to that in 405 nm and 521 nm lasers.

The position sensitivity ($S_p = \Delta V_{AB}/\Delta X$) of the heterostructure is shown in Figure 5b. The sensitivity increases significantly from 6.5 mV/mm to 30.7 mV/mm when the illumination intensity is changed from 23 mW/cm² to 7.4 W/cm² (635 nm). Thereafter, the dependency becomes slower (from 7.4 W/cm² to 1.0 W/cm²) until it saturates at approximately

1.25 W/cm² (635 nm). The saturation behaviour may be attributed to the Auger process which becomes dominant at higher intensities, resulting in a decrease in the photocarriers lifetime and thus, the carrier's extraction probability in the external circuit decreases.⁴⁷ In addition, at high intensities, the $e_{ph} - h_{ph}$ recombination rate increases considerably at the region of laser illumination, which also plays a crucial role in the observed saturation behaviour.^{48,49} The influence of the thermo activated resistive effect in the Si-substrate on the observed LPV is also investigated (Figure S4, supporting information). The results indicate that, under the visible light illuminations, the observed lateral photovoltaic effect is solely due to the $e_{ph} - h_{ph}$ generation and separation mechanism near the heterojunction rather than the thermo activated resistive effect in the Si-substrate.

Furthermore, it is found that both V_{AB} and S_p do not change significantly up to 323 K, and then they decrease more than one order of magnitude at 423 K compared to that in 298 K (Figures 6a,b). The observed trend can be discussed as follows. The temperature dependence of the lateral photovoltage effect of a SiC/Si heterostructure, under optical illumination (635 nm), mainly depends on the carrier concentration in the Si substrate. The carrier concentration as a function of temperature can be defined as:⁴⁴

$$n = T^{3/2} \exp\left(-\frac{E_a}{k_B T}\right) \quad (2)$$

where E_a and k_B are the activation energy and Boltzmann constant, respectively. In addition, the light illumination provides a photon energy to excite charge carriers in the Si-substrate, which causes the lateral gradient of charge carriers in the SiC layer. When the temperature increases, more charge carriers are excited by the thermal energy in the Si-substrate. This leads to a smaller number of charge carriers generated by light illuminations, as shown schematically in Figure 6c. The thermal energy becomes dominant at high temperatures and limits the generation of photoexcited $e_{ph} - h_{ph}$ pairs near the illuminated area, hence resulting in a small gradient of charge carriers in the 3C-SiC layer. Therefore, as shown in Figure 6d, the lateral photovoltage decreases with the increasing temperature.

Figure 6: Temperature-dependent photo-characteristics of the 3C-SiC/Si heterostructure. (a) Lateral photovoltage (V_{AB}) and (b) position sensitivity (S_p) as a function of temperature at different intensities (635 nm, spot position (X, Y): (+3.2 mm, 0)), (c) carrier distribution mechanism at high temperatures under illumination conditions, and (d) stable and repeatable V_{AB} at different temperatures under an illumination of 635 nm with an intensity of 0.9 W/cm² and the laser position (X, Y) is at (+3.0 mm, 0). Colored and white areas represent light ON and OFF conditions, respectively.

For these reasons, the sensitivity of 3C-SiC/Si decreases from 33.0 mV/mm to 3.7 mV/mm when the temperature changes from 298 K to 423 K under a constant illumination of 2.8 W/cm² (635 nm), as shown in Figure 6b.

In order to identify the exact laser spot position on a plane, a 3C-SiC/Si with four contacts has been fabricated. Figures 7a and 7b show the 2D-mapping of the lateral photovoltages, V_{AB} and V_{CD} , as a function of laser spot positions under an illumination of 23 mW/cm² (635 nm) where the laser is scanned spatially along the X-axis. As discussed earlier, Figure 7a

Figure 7: 2D-mapping of the lateral photovoltages (a) V_{AB} and (b) V_{CD} , (c) precise spot positioning by measuring both V_{AB} and V_{CD} simultaneously, and (d) full mapping of the laser spot positions on a plane.

indicates that the V_{AB} is negative, zero, and positive when the spot position is at $-X$, 0 , and $+X$, respectively. In contrast, when V_{CD} is measured for different positions of X at a constant Y , then it reaches its maximum at $X=0$ and shows an approximately symmetric behaviour in both sides of $X=0$ (Figure 7b). The characteristic is attributed to the fact that, for instance, when the laser is at $(0, -1)$, the spot position is closed to the C electrode and hence more photogenerated holes reach this electrode and thus the E_{F-SiC} moves downward compared to that at the D electrode, resulting in the V_{CD} reaching its maximum (negatively) at this position. However, if the laser spot moves away from the $X = 0 \text{ mm}$ (Y remains constant at -1 mm), for example, at $X = -2 \text{ mm}$, V_{CD} reduces to -7.0 mV from -12.9 mV (Figure 7b), which is attributed to the decrease in photocarrier distribution at electrode C. By measuring V_{AB} and V_{CD} simultaneously, it is possible to detect the location of laser spot precisely on a XY plane. If only V_{AB} is measured, for instance, the position of the laser spot is at $(X,$

Table 1: Performance comparison of the proposed 3C-SiC/Si heterostructure with the reported self-powered heterojunction-based PSDs.

Device	Rectification Ratio (I_F/I_R)	Wavelengths (nm)	Sensitivity (mV/mm)	Limit of contact distance for a linear response (mm)	Ref.
ITO/MoS ₂ /p-Si	2	405-980	42.3	1	19
Ag/TrGOF	-	633	0.02	~ 5	50
NdNiO ₃ /Nb:SrTiO ₃	-	266	32	2	20
Cu ₂ O/SiO ₂	-	2000	15	4	51
Fe ₃ O ₄ /3C-SiC	-	405	67.8	4	52
3C-SiC/Si	3.7×10^4	405-635	33	7	This work

$Y) = (2, 1)$ and $(2, -1)$, in both cases $V_{AB} = 7.0$ mV, hence it is not possible to distinguish between two laser spot locations. In contrast, when both are measured simultaneously, then $(V_{AB}, V_{CD}) = (7.0 \text{ mV}, 3.0 \text{ mV})$ and $(7.0 \text{ mV}, -3.0 \text{ mV})$ at $(X, Y) = (2, 1)$ and $(2, -1)$, respectively, as shown in Figure 7c. From the 2D-mapping of V_{AB} and V_{CD} , the polarity of V_{AB} and V_{CD} are summarized in Figure 7d, which clearly indicates that the position of laser spots can be detected precisely when both V_{AB} and V_{CD} are measured simultaneously. Table 1 summarized the photonic properties of the proposed 3C-SiC/Si heterojunction position sensitive detector compared to the reported heterojunction based self-powered PSDs. The linear dependency of LPE, in the 3C-SiC/Si heterostructure, over a large distance between two contacts (A and B) offers clear advantages with respect to the reported heterojunction-based PSDs as the region with a linear dependency of LPE is only usable for PSDs.¹⁸ Moreover, other properties such as rectification ratio, sensitivity, and detection range are also comparable with the reported PSDs.

Conclusion

In conclusion, the fabrication and characterisation of a 3C-SiC/Si heterostructure based on four-terminals position sensitive detector have been reported. The structure exhibits substantial position sensitivity with excellent linearity, stability, and repeatability. The experimental results at different spot positions and temperatures, and under various illumination

conditions (i.e., intensities and wavelengths) have been explained in-details using the energy band analysis. It is observed that it is possible to identify the exact location of the laser spot by measuring both V_{AB} and V_{CD} simultaneously. By utilizing the advantages of a relatively simple and cost-effective device configuration (3C-SiC fully covered the Si-substrate and no requirement of complicated device fabrication process), the proposed heterostructure could be a promising option for position sensitive detector in harsh environments, such as highly corrosive environments.

Acknowledgement

This work was performed in part at the Griffith node of the Australian National Fabrication Facility. A company was established under the National Collaborative Research Infrastructure Strategy to provide nano- and microfabrication facilities for Australia's researchers. This work was partially funded by the linkage grant (LP160101553) from the Australian Research Council (ARC).

Supporting Information Available

Device fabrication procedures are discussed in Figure S1 and a schematic of the experimental setup is shown in Figure S2. In addition, vertical I-V and C-f characteristics of the heterojunction is shown in Figure S3, and the thermo resistive effect in the Si(100)-substrate under different illumination conditions is presented in Figure S4. The surface roughness of the 3C-SiC film is shown in Figure S5.

References

- (1) Opdorp, C. V.; Kanerva, H. K. Current-voltage Characteristics and Capacitance of Isotype Heterojunctions. *Solid-State Electron.* **1967**, *10*, 401–21.

- (2) Kroemer, H. *Electronic Structure of Semiconductor Heterojunctions*. Springer, Dordrecht, **1988**, 116–149.
- (3) Zeng, L. H.; Lin, S. H.; Li, Z. J.; Zhang, Z. X.; Zhang, T. F.; Xie, C.; Mak, C. H.; Chai, Y.; Lau, S. P.; Luo, S. P.; Tsang, Y. H. Fast, Self-Driven, Air-Stable, and Broadband Photodetector Based on Vertically Aligned PtSe₂/GaAs Heterojunction. *Adv. Funct. Mater.* **2018**, *28*, 1705970.
- (4) Guo, X. C.; Hao, N. H.; Guo, D. Y.; Wu, Z. P.; An, Y. H.; Chu, X. L.; Li, L. H.; Li, P. G.; Lei, M.; Tang, W. H. β -Ga₂O₃/p-Si Heterojunction Solar-Blind Ultraviolet Photodetector with Enhanced Photoelectric Responsivity. *J. Alloy Compd.* **2016**, *660*, 136–140.
- (5) Jo, S. H.; Lee, H. W.; Shim, J.; Heo, K.; Kim, M.; Song, Y. J.; Park, J. H. Highly Efficient Infrared Photodetection in a Gate-Controllable Van der Waals Heterojunction with Staggered Bandgap Alignment. *Adv. Sci.* **2018**, *4*, 1700423.
- (6) Yang, J.; Kwak, H.; Lee, Y.; Kang, Y. S.; Cho, M. H.; Cho, J. H.; Kim, Y. H.; Jeong, S. J.; Park, S.; Lee, H. J.; Kim, H. MoS₂-InGaZnO Heterojunction Phototransistors with Broad Spectral Responsivity. *ACS Appl. Mater. Interfaces* **2016**, *8*, 8576–8582.
- (7) Chang, G. E.; Basu, R.; Mukhopadhyay, B.; Basu, P. K. Design and Modeling of GeSn-based Heterojunction Phototransistors for Communication Applications. *IEEE J. Sel. Top Quantum Electron.* **2016**, *22*, 425–433.
- (8) Kao, T. T.; Kim, J.; Detchprohm, T.; Dupuis, R. D.; Shen, S. C. High-Responsivity GaN/InGaN Heterojunction Phototransistors. *IEEE Photonic Tech. L.* **2016**, *28*, 2035–2038.
- (9) Tsai, M. L.; Li, M. Y.; Retamal, J. R.; Lam, K. T.; Lin, Y. C.; Suenaga, K.; Chen, L. J.; Liang, G.; Li, L. J.; He, J. H. Single Atomically Sharp Lateral Monolayer PN

- Heterojunction Solar Cells with Extraordinarily High Power Conversion Efficiency. *Adv. Mater.* **2017**, *29*, 1701168.
- (10) Yoshikawa, K.; Kawasaki, H.; Yoshida, W.; Irie, T.; Konishi, K.; Nakano, K.; Uto, T.; Adachi, D.; Kanematsu, M.; Uzu, H.; Yamamoto, K. Silicon Heterojunction Solar Cell with Interdigitated Back Contacts for a Photoconversion Efficiency over 26%. *Nat. Energy* **2017**, *2*, 17032.
 - (11) Pradhan, S. K.; Xiao, B.; Pradhan, A. K. Enhanced Photo-Response in P-Si/MoS₂ Heterojunction-based Solar Cells. *Sol. Energy Mater. Sol. Cells* **2016**, *144*, 117–127.
 - (12) Wang, X.; Zhao, X.; Hu, C.; Zhang, Y.; Song, B.; Zhang, L.; Liu, W.; Lv, Z.; Zhang, Y.; Tang, J.; Sui, Y. Large Lateral Photovoltaic Effect with Ultrafast Relaxation Time in SnSe/Si Junction. *Appl. Phys. Lett.* **2016**, *109*, 023502.
 - (13) Hu, C.; Wang, X.; Miao, P.; Zhang, L.; Song, B.; Liu, W.; Lv, Z.; Zhang, Y.; Sui, Y.; Tang, J.; Yang, Y. Origin of the Ultrafast Response of the Lateral Photovoltaic Effect in Amorphous MoS₂/Si Junctions. *ACS Appl. Mater. Interfaces* **2017**, *9*, 18362–18368.
 - (14) Tabatabaie, N.; Meynadier, M. H.; Nahory, R. E.; Harbison, J. P.; Florez, L. T. Large Lateral Photovoltaic Effect in Modulation-Doped AlGaAs/GaAs Heterostructures. *Appl. Phys. Lett.* **1989**, *55*, 792–794.
 - (15) Xu, T.; Han, Y.; Lin, L.; Xu, J.; Fu, Q.; He, H.; Song, B.; Gai, Q.; Wang, X. Self-Power Position-Sensitive Detector with Fast Optical Relaxation Time and Large Position Sensitivity Basing on the Lateral Photovoltaic Effect in Tin Diselenide Films. *J. Alloy Compd.* **2019**, *790*, 941–946.
 - (16) Huang, X.; Mei, C.; Gan, Z.; Zhou, P.; Wang, H. Lateral Photovoltaic Effect in P-type Silicon Induced by Surface States. *Appl. Phys. Lett.* **2017**, *110*, 121103.

- (17) Wang, W.; Yan, Z.; Zhang, J.; Lu, J.; Qin, H.; Ni, Z. High-Performance Position-Sensitive Detector Based on Graphene-Silicon Heterojunction. *Optica* **2018**, *5*, 27–31.
- (18) Yu, C.; Wang, H. Large Lateral Photovoltaic Effect in Metal-(Oxide-) Semiconductor Structures. *Sensors* **2010**, *10*, 10155–10180.
- (19) Qiao, S.; Zhang, B.; Feng, K.; Cong, R.; Yu, W.; Fu, G.; Wang, W. Large Lateral Photovoltage Observed in MoS₂ Thickness-Modulated ITO/MoS₂/p-Si Heterojunctions. *ACS Appl. Mater. Interfaces* **2017**, *9*, 18377–18387.
- (20) Wang, X.; Zhou, Q.; Li, H.; Hu, C.; Zhang, L.; Zhang, Y.; Zhang, Y.; Sui, Y.; Song, B. Self-Powered Ultraviolet Vertical and Lateral Photovoltaic Effect with Fast-Relaxation Time in NdNiO₃/Nb:SrTiO₃ Heterojunctions. *Appl. Phys. Lett.* **2018**, *112*, 122103.
- (21) Dinh, T.; Phan, H.-P.; Nguyen, T.-K.; Balakrishnan, V.; Cheng, H. H.; Hold, L.; Lacopi, A.; Nguyen, N.-T.; Dao, D. V. Unintentionally Doped Epitaxial 3C-SiC (111) Nanothin Film as Material for Highly Sensitive Thermal Sensors at High Temperatures. *IEEE Electron Device Lett.* **2018**, *39*, 580–583.
- (22) Buetow, S.; Herzer, R.; Koenigsmann, G.; Rossberg, M.; Maul, A. High Power, High Frequency SiC-MOSFET System with Outstanding Performance, Power Density and Reliability. In *29th Int. Symp. Power Semi. Devices IC's (ISPSD)*, **2017**, 419–422.
- (23) Du, Y.; Wang, J.; Wang, G.; Huang, A. Q. Modeling of the High-Frequency Rectifier With 10-kV SiC JBS Diodes in High-Voltage Series Resonant Type DC-DC Converters. *IEEE Trans. Power Electron.* **2013**, *29*, 4288–4300.
- (24) Phan, H.-P.; Dao, D. V.; Nakamura, K.; Dimitrijević, S.; Nguyen, N.-T. The Piezoresistive Effect of SiC for MEMS Sensors at High Temperatures: a Review. *J. Microelectromech. S.* **2015**, *24*, 1663–1677.

- (25) Tanner, P.; Iacopi, A.; Phan, H.-P.; Dimitrijević, S.; Hold, L.; Chaik, K.; Walker, G.; Dao, D. V.; Nguyen, N.-T. Excellent Rectifying Properties of the n-3C-SiC/p-Si Heterojunction Subjected to High Temperature Annealing for Electronics, MEMS, and LED Applications. *Sci. Rep.* **2017**, *7*, 17734.
- (26) Wang, V.; Dimitrijević, S.; Han, J.; Tanner, P.; Iacopi, A.; Hold, L. Demonstration of p-Type 3C-SiC Grown on 150 mm Si (1 0 0) Substrates by Atomic-Layer Epitaxy at 1000 °C. *J. Cryst. Growth* **2011**, *329*, 67–70.
- (27) Phan, H.-P.; Dao, D. V.; Wang, L.; Dinh, T.; Nguyen, N.-T.; Qamar, A.; Tanner, P.; Dimitrijević, S.; Zhu, Y. The Effect of Strain on the Electrical Conductance of P-Type Nanocrystalline Silicon Carbide Thin Films. *J. Mater. Chem. C* **2015**, *3*, 1172–1176.
- (28) Foissal, A. R. M.; Qamar, A.; Phan, H.-P.; Dinh, T.; Nguyen, T.-K.; Panner, P.; Streed, E. W.; Dao, D. V. Pushing the Limits of Piezoresistive Effect by Optomechanical Coupling in 3C-SiC/Si Heterostructure. *ACS Appl. Mater. Interfaces* **2017**, *9*, 39921–39925.
- (29) Phan, H.-P.; Dinh, T.; Kozeki, T.; Nguyen, T.-K.; Qamar, A.; Namazu, T.; Nguyen, N.-T.; Dao, D. V. Nano Strain-Amplifier: Making Ultra-Sensitive Piezoresistance in Nanowires Possible without the Need of Quantum and Surface Charge Effects. *Appl. Phys. Lett.* **2016**, *109*, 123502.
- (30) Young, D. J.; Du, J.; Zorman, C. A.; Ko, W. H. High-Temperature Single-Crystal 3C-SiC Capacitive Pressure Sensor. *IEEE Sens. J.* **2004**, *4*, 464–470.
- (31) Mehregany, M.; Tong, L.; Matus, L. G.; Larkin, D. J. Internal Stress and Elastic Modulus Measurements on Micromachined 3C-SiC Thin Films. *IEEE Trans. Electron Devices* **1997**, *44*, 74–79.
- (32) Calusine, G.; Politi, A.; Awschalom, D. D.; Silicon Carbide Photonic Crystal Cavities with Integrated Color Centers. *Appl. Phys. Lett.* **2014**, *105*, 011123.

- (33) Massoubre, D.; Wang, L.; Hold, L.; Fernandes, A.; Chai, J.; Dimitrijević, S.; Iacopi, A. Vertically Conductive Single-Crystal SiC-Based Bragg Reflector Grown on Si Wafer. *Sci. Rep.* **2015**, *5*, 17026.
- (34) Miyajima, S.; Irikawa, J.; Yamada, A.; Konagai, M.; High-Quality Nanocrystalline Cubic Silicon Carbide Emitter for Crystalline Silicon Heterojunction Solar Cells. *Appl. Phys. Lett.* **2010**, *97*, 023504.
- (35) Syväjärvi, M.; Ma, A.; Jokubavicius, V.; Galeckas, A.; Sun, J.; Liu, X.; Jansson, M.; Wellmann, P.; Linnarsson, M.; Runde, P.; Johansen, B. A.; Cubic Silicon Carbide as a Potential Photovoltaic Material. *Sol. Energy Mater. Sol. Cells* **2016**, *145*, 104–108.
- (36) Tonisch, K.; Jatal, W.; Niebelschuetz, F.; Romanus, H.; Baumann, U.; Schwierz, F.; Pezoldt, J. AlGaIn/GaN-heterostructures on (111) 3C-SiC/Si Pseudo Substrates for High Frequency Applications. *Thin Solid Films* **2011**, *520*, 491–496.
- (37) Lin, C. M.; Lien, W. C.; Felmetsger, V. V.; Hopcroft, M. A.; Senesky, D. G.; Pisano, A. P. AlN Thin Films Grown on Epitaxial 3C-SiC (100) for Piezoelectric Resonant Devices. *Appl. Phys. Lett.* **2010**, *97*, 141907.
- (38) Massoubre, D.; Wang, L.; Chai, J.; Walker, G.; Hold, L.; Lobino, M.; Dimitriev, S.; Iacopi, A. Single-Crystalline 3C-SiC Thin-Film on Large Si Substrate For Photonic Applications. *NSTI-Nanotech* **2014**, 416–419.
- (39) Anzalone, R.; Litrico, G.; Piluso, N.; Reitano, R.; Alberti, A.; Fiorenza, P.; Coffa, S.; and La Via, F. Carbonization and transition layer effects on 3C-SiC film residual stress. *J. Cryst. Growth* **2017**, *473*, 11–19.
- (40) Zhang, Y.; Zhang, Y.; Yao, T.; Hu, C.; Sui, Y.; Wang, X. Ultrahigh Position Sensitivity and Fast Optical Relaxation Time of Lateral Photovoltaic Effect in Sb₂Se₃/p-Si junctions. *Opt. Express* **2018**, *26*, 34214–34223.

- (41) Qiao, S.; Zhang, B.; Feng, K.; Cong, R.; Yu, W.; Fu, G.; Wang, S. Large Lateral Photovoltage Observed in MoS₂ Thickness-Modulated ITO/MoS₂/p-Si Heterojunctions. *ACS Appl. Mater. Interfaces* **2017**, *9*, 18377–18387.
- (42) Phan, H.-P.; Nguyen, T.-K.; Dinh, T.; Iacopi, A.; Hold, L.; Shiddiky, M. J.; Dao, D. V.; Nguyen, N.-T. Robust Free-Standing Nano-Thin SiC Membranes Enable Direct Photolithography for MEMS Sensing Applications. *Adv. Eng. Mater.* **2018**, *20*, 1700858.
- (43) Ibn-Mohammed, T.; Koh, S. C.; Reaney, I. M.; Acquaye, A.; Schileo, G.; Mustapha, K. B.; Greenough, R. Perovskite Solar Cells: an Integrated Hybrid Lifecycle Assessment and Review in Comparison with other Photovoltaic Technologies. *Renew. Sust. Energ. Rev.* **2017**, *80*, 1321–1344.
- (44) Sze, S. M.; Ng, K. K. *Physics of Semiconductor Devices*, John Wiley & Sons: New York, 2007.
- (45) Sai, H.; Matsui, T.; Koida, T.; Matsubara, K.; Kondo, M.; Sugiyama, S.; Katayama, H.; Takeuchi, Y.; Yoshida, I. Triple-Junction Thin-Film Silicon Solar Cell Fabricated on Periodically Textured Substrate with a Stabilized Efficiency Of 13.6%. *Appl. Phys. Lett.* **2015**, *106*, 213902.
- (46) Goldschmidt, J. C.; Do, C.; Peters, M.; Goetzberger, A. Spectral Splitting Module Geometry that Utilizes Light Trapping. *Sol. Energy Mater. Sol. Cells* **2013**, *108*, 57–64.
- (47) Yu, P.; Yu, X.; Lu, W.; Lin, H.; Sun, L.; Du, K.; Liu, F.; Fu, W.; Zeng, Q.; Shen, Z.; Jin, C. Fast Photoresponse from 1T Tin Diselenide Atomic Layers. *Adv. Funct. Mater.* **2016**, *26*, 137–145.
- (48) Huang, X.; Mei, C.; Gan, Z.; Zhou, P.; Wang, H. Lateral Photovoltaic Effect in P-Type Silicon Induced by Surface States. *Appl. Phys. Lett.* **2017**, *110*, 121103.

- (49) Hu, C.; Wang, X.; Miao, P.; Zhang, L.; Song, B.; Liu, W.; Lv, Z.; Zhang, Y.; Sui, Y.; Tang, J.; Yang, Y. Origin of the Ultrafast Response of the Lateral Photovoltaic Effect in Amorphous MoS₂/Si Junctions. *ACS Appl. Mater. Interfaces* **2017**, *9*, 18362–18368.
- (50) Moon, I.K.; Ki, B.; Yoon, S.; Choi, J.; Oh, J. Lateral photovoltaic effect in flexible free-standing reduced graphene oxide film for self-powered position-sensitive detection. *Sci. Rep.* **2016**, *6*, 33525.
- (51) Du, L.; Wang, H. Infrared laser induced lateral photovoltaic effect observed in Cu₂O nanoscale film. *Opt. Exp.* **2010**, *18*, 9113–9118.
- (52) Song, B.; Wang, X.; Li, B.; Zhang, L.; Lv, Z.; Zhang, Y.; Wang, Y.; Tang, J.; Xu, P.; Li, B.; Yang, Y. Near-ultraviolet lateral photovoltaic effect in Fe₃O₄/3C-SiC schottky junctions. *Opt. Exp.* **2016**, *24*, 23755-23764.

Graphical TOC Entry