ISSN: 2414-1895 DOI: 10.6919/ICJE.202603_12(3).0003

Near-Infrared Self-Powered Photodetector based on Graphene/Si Heterojunction

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Abstract

High-performance self-powered infrared photodetectors that operate without consuming external power are of great significance for applications in optical communication, sensing, and motion detection. Herein, we constructed a vertical Graphene/Si heterojunction. Benefiting from the structural design and interface purification, the device exhibits a significantly enhanced self-powered photocurrent response and near-infrared detection capability. It demonstrates a responsivity of 5.55 A/W and a specific detectivity of 4.62 × 1012 Jones at 808 nm, along with a fast response time of 5.5/7.2 μs. Furthermore, the device retains its performance without degradation after 200 days, exhibiting stable temporal response characteristics and long-term repeatability. These results suggest that this heterostructure provides an effective strategy for high-performance self-powered infrared photodetectors.

Keywords

Graphene/Si Heterojunction; Self-Powered; Near-Infrared Photodetection.

1. Introduction

Photodetector is a device that converts incident photons into quantifiable electrical signals. Owing to their ultrafast response speed and high responsivity, photodetectors hold significant application value and demonstrate great potential in diverse fields such as optical communication,[1] sensing,[2] motion detection,[3] missile warning,[4] and biomedical imaging.[5] Currently, the vast majority of photodetectors require an external power source to drive the relaxation of photogenerated carriers and generate photocurrent. However, this operational mode severely restricts their application and development in numerous areas, including in situ medical monitoring and wireless environmental sensing.[6-8] Consequently, the development of self-powered photodetectors capable of operating without an external power supply has emerged as a key research focus for many scholars.[9-10] Conventional self-powered photodetectors based on bulk materials often suffer from large dimensions and relatively complex systems, making it difficult to simultaneously meet the stringent requirements of high performance and lightweight design.[11] This has become a technical bottleneck limiting their application in portable and airborne systems. In contrast, photodetectors based on Schottky heterojunctions, which typically operate in a self-powered mode due to the strong photovoltaic effect arising from their substantial built-in potential difference, have emerged as a promising platform for exploring self-powered photodetection. Furthermore, they exhibit tremendous application potential owing to their simple fabrication process, low cost, compact structure, compatibility with CMOS technology, and broadband photodetection capabilities.[12-13]

Two-dimensional (2D) materials, with their rich electrical and optical properties and the unique advantage of a dangling-bond-free surface, enable the direct stacking of 2D materials with different

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DOI: 10.6919/ICJE.202603_12(3).0003

band alignments and physical properties without lattice mismatch constraints. This provides an ideal platform for constructing next-generation high-performance novel photodetectors[14-15] . Among them, graphene (Gr) has emerged as an attractive material for optoelectronic devices due to its ultrahigh carrier mobility, broadband absorption spanning from the ultraviolet to the far-infrared region, and excellent ultrafast photoresponse characteristics[16-17] . However, the development of Gr-based photodetectors still faces performance bottlenecks arising from its intrinsic properties. Specifically, these include the relatively low absorption cross-section of graphene, its zero bandgap, the lack of a gain mechanism, and ultrafast carrier recombination on the picosecond timescale. These factors collectively constrain the efficient collection and conversion of photogenerated carriers, resulting in the consistently low photoresponsivity of pristine graphene detectors[18].

To address the aforementioned issues, integrating graphene with semiconductor materials such as silicon (Si) to form Schottky heterojunctions presents an effective strategy for constructing high-performance photodetectors.[19-22] In such heterostructures, the substantial difference in Fermi levels induces a significant Schottky barrier, enabling rapid and efficient separation and relaxation of photogenerated carriers. This mechanism compensates for the inherent limitations of graphene, including its zero bandgap and weak optical absorption, thereby successfully achieving efficient and ultrafast photoelectric conversion. In recent years, considerable progress has been made in the study of photodetectors based on Schottky heterojunctions. In early research, Chen et al. observed the Schottky diode characteristics of Gr/Si heterojunctions.[23] Subsequently, Thomay et al. further enhanced the transport properties of these heterojunctions.[24] Building on this foundation, Zhu et al. developed a vertical photodetector based on reduced graphene oxide and Si achieving a maximum responsivity of 63 $mA\cdot W^{-1}$ under 445 nm laser illumination and an excellent on/off ratio as high as 6.25×10^4.[25] Despite these notable advancements, exploration of photodetection in the infrared region and under self-powered operating modes remains insufficient.

In this work, a self-powered photodetector based on a Gr/Si Schottky heterojunction was fabricated. Few-layer graphene was employed as the conductive layer, effectively reducing optical transmission loss at the interface. Furthermore, a circular electrode configuration was introduced to enlarge the active area and shorten the relaxation path of photogenerated carriers. This synergistic design strategy enables a significantly enhanced self-powered photoresponse in the near-infrared region, achieving an ultrahigh responsivity of 5.55 A/W at 808 nm, a specific detectivity as high as 4.62×10^{12} Jones, and a fast response time (τ_{rise}/τ_{decay}) of 5.5/7.2 μs. The Gr/Si Schottky junction photodetector demonstrates excellent response to near-infrared illumination while operating in self-powered mode, along with outstanding long-term repeatability and robustness. This work offers an effective strategy for the development of high-performance self-powered infrared photodetectors.

2. Result and Discussion

A schematic illustration of the fabrication process for the Gr/Si vertical van der Waals heterojunction photodetector is shown in **Figure 1a**. On a p-type silicon substrate (thickness: 150 μm, resistivity: 1-10 Ω·cm) covered with a 100 nm thick SiO_2 layer, a circular window with a diameter of 100 μm was defined using photolithography, and the SiO_2 layer within the window was selectively removed to expose the underlying silicon surface. Subsequently, a second patterning process was performed to form electrode patterns around the window. Finally, a few-layer graphene film grown by chemical vapor deposition was transferred onto the substrate using a classic wet transfer technique, forming a high-quality Schottky heterojunction with Si. An optical microscopy (OM) image of the Gr/Si photodetector is presented in **Figure 1b**, showing that the Ti/Au electrodes and the underlying silicon window are fully covered by the top graphene layer. This configuration effectively prevents direct contact between the metal and silicon, thereby mitigating the influence of Fermi level pinning and excessive interfacial contact potential difference on the photoresponse. Meanwhile, the high carrier mobility of graphene facilitates rapid transport and collection of photogenerated carriers, enabling excellent photodetection performance. Atomic force microscopy (AFM) was employed to characterize the surface morphology and thickness of the transferred graphene film (**Figure 1c**). It

International Core Journal of Engineering
ISSN: 2414-1895
Volume 12 Issue 3, 2026
DOI: 10.6919/ICJE.202603_12(3).0003

can be clearly observed that the graphene film exhibits a smooth surface with no obvious contaminants, and its thickness is only 2.71 nm. Raman spectroscopy was utilized to assess the material quality and crystal structure. The Raman spectrum collected from the graphene film is shown in **Figure 1d**. Two prominent characteristic peaks are observed at 1580 cm^{-1} and 2680 cm^{-1}, corresponding to the G band and 2D band of graphene, respectively.[22, 26] The intensity ratio and lineshape of these peaks indicate that the prepared graphene is monolayer or few-layer with minimal defects and high quality, which is consistent with the AFM characterization results. While maintaining a relatively high carrier mobility, few-layer graphene avoids the reduction in optical transmittance and degradation in carrier transport performance associated with excessive layer numbers, enabling more efficient photoelectric conversion in the device compared to multilayer graphene.

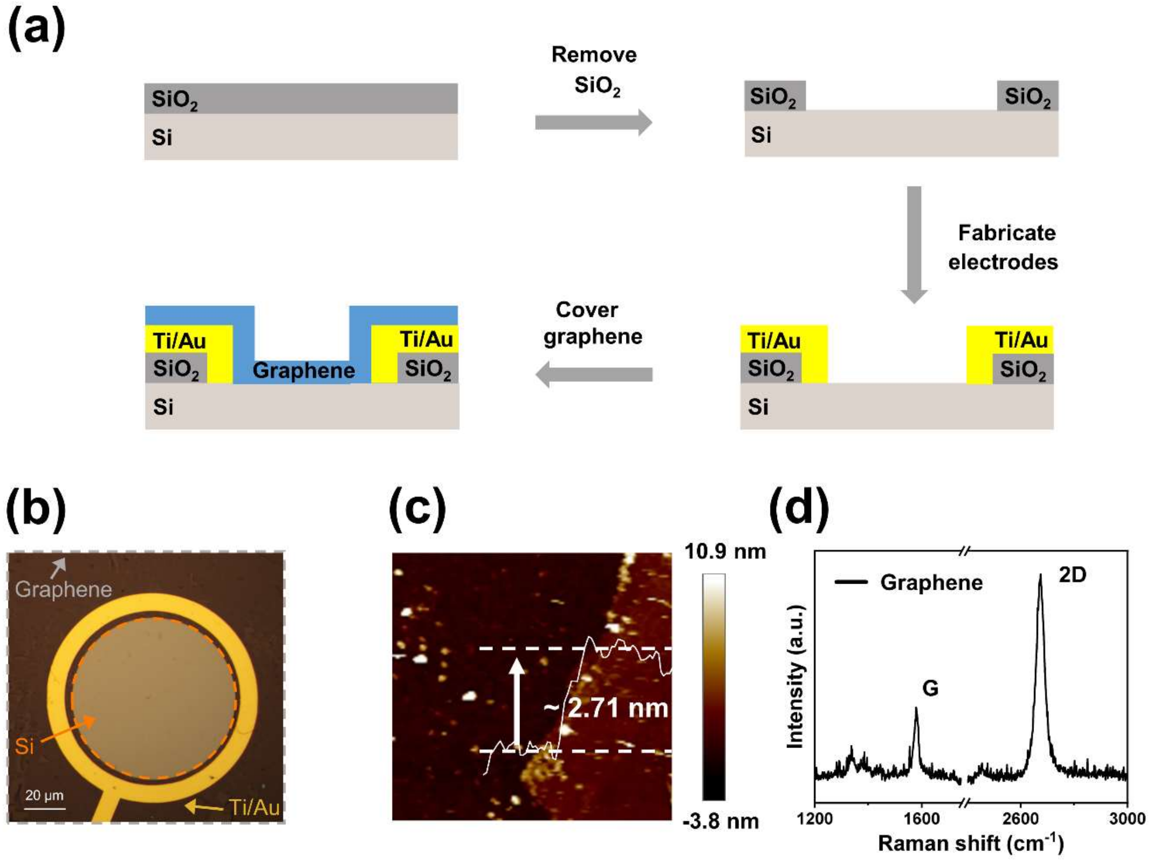

Figure 1. Schematic diagram and characterization of the fabrication process of Gr/Si device. (a) Schematic diagram of the device fabrication process. (b) Optical microscope image of the device. (c) AFM image of graphene. (d) Raman spectrum of graphene.

Based on the excellent photodetection potential of the Gr/Si heterojunction device, its photoelectric performance was characterized in detail. **Figures 2a-b** displays the current-voltage (*I-V*) characteristic curves of the device under dark conditions and upon illumination with 808 nm and 1064 nm lasers. The asymmetric shape of the *I-V* curves is attributed to the Schottky contact formed at the Gr/Si heterojunction. The photocurrent exhibited a clear increasing trend with rising optical power for all measurements, demonstrating that photogenerated carriers are efficiently separated and rapidly collected at the heterojunction interface. The leftward shift of the curves with increasing power highlights a pronounced photovoltaic effect, underscoring the device's excellent photoresponse in self-powered mode, which aligns well with our device design principles. Under 808 nm near-infrared illumination (86.1 mW/cm^2), the device yielded an open-circuit voltage (V_{OC}) of 0.29 V and a short-

ISSN: 2414-1895 DOI: 10.6919/ICJE.202603_12(3).0003

circuit current (I_{SC}) of 0.86 μA. **Figure 2c** shows the variation of the output electrical power (P_{el}) as a function of bias voltage. The power conversion efficiency (*PCE*) of the device at zero bias was calculated to be 3.69%, confirming its efficient operation in self-powered photovoltaic mode. Furthermore, **Figures 2d-e** presents the time-resolved photoresponse of the device under self-powered conditions when illuminated at 808 nm and 1064 nm. The results indicate that the device exhibits a high photoresponse in self-powered mode, generating a maximum photocurrent of 731.1 nA and 182.1 nA under 808 nm and 1064 nm illumination, respectively, while maintaining a dark current (I_{dark}) at the picoampere level. This self-powered capability originates from the robust built-in electric field within the Schottky junction, formed by the work function difference between graphene and silicon, which enables rapid separation of photogenerated carriers. Concurrently, the ultrahigh carrier mobility of graphene further enhances carrier transport and collection efficiency. This synergistic mechanism endows the device with excellent photovoltaic detection performance in the near-infrared region.

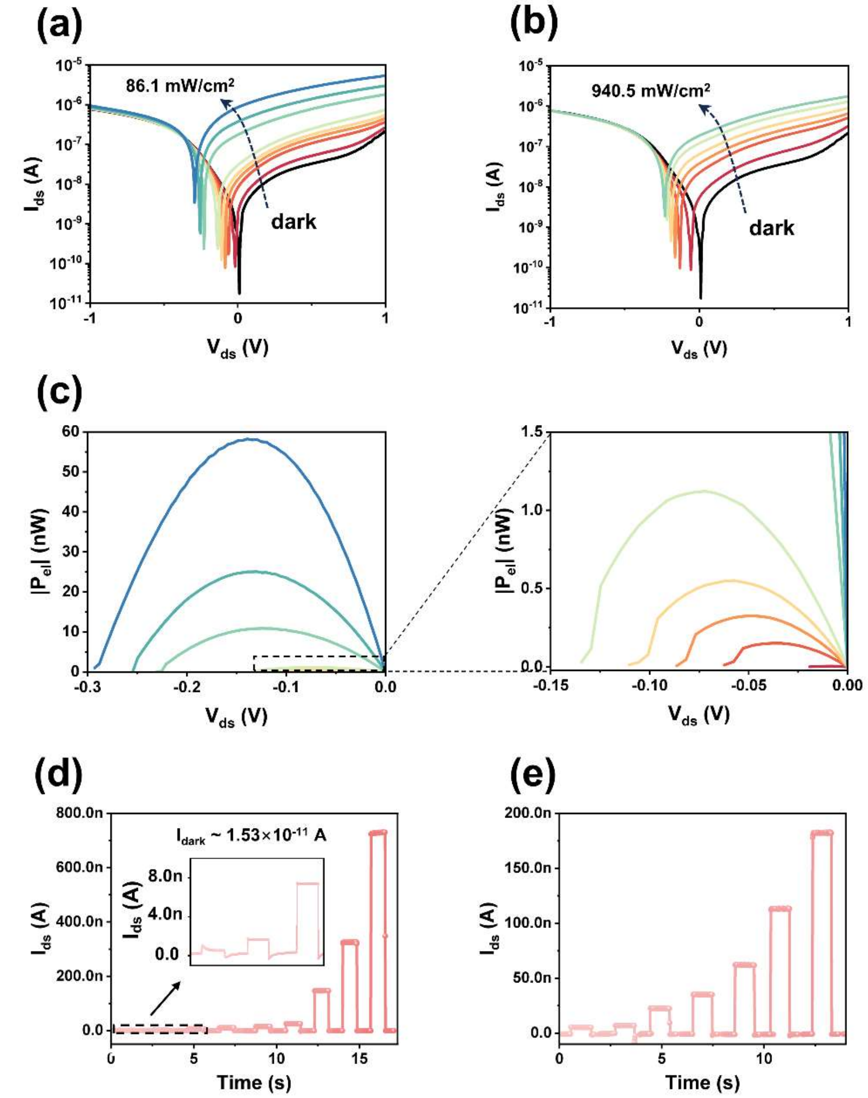

Figure 2. Photoresponse characteristics of Gr/Si photodetectors. (a-b) I_{ds}-V_{ds} characteristic curves of the device under (a) 808 nm and (b) 1064 nm laser irradiation. (c) Schematic diagram of output electrical power P_{el} as a function of V_{ds}. (d) Self-powered photoswitching curves under 808 nm light irradiations. Attached figure: Zoomed display of the low power region marked by the dashed rectangular box. (e) Self-powered photoswitching curves under 1064 nm light irradiations.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202603_12(3).0003

Key performance metrics were quantified to assess the overall photoresponse sensitivity. The responsivity (*R*) and specific detectivity (D^*) are summarized in **Figure 3a**. Under 808 nm illumination, the Gr/Si device exhibits significantly enhanced photoelectric conversion capability. At zero bias, it achieves a high *R* of 5.55 A/W and a D^* of 4.62×10^{12} Jones. As shown in **Figure 3b**, the on/off ratio (I_{on}/I_{off}) and *Gain* reach exceptional values of 4.88×10^4 and 8.54, respectively. All parameters exhibit an inverse relationship with light intensity, attributed to the screening effect induced by excess photocarriers under high-intensity illumination.[27] Noise analysis reveals frequency-dependent behavior of the device (**Figure 3c**). Based on the measured noise current spectra, the noise equivalent power (*NEP*) values for the Gr/Si device were calculated, as presented in **Figure 3d**. The *NEP* shows an inverse relationship with illumination intensity, reaching as low as 3.11 fW/Hz$^{1/2}$ at low power densities. This indicates that the device can distinguish weak signals as low as 3.11 fW from noise. The device also demonstrates fast response time, with a rise/decay time (τ_{rise}/τ_{decay}) of 5.5/7.2 μs (**Figure 3e**). Furthermore, the device retains its performance without degradation after 100 and 200 days of storage, as shown in **Figure 3f**. This highlights its reliability and suitability for practical applications.

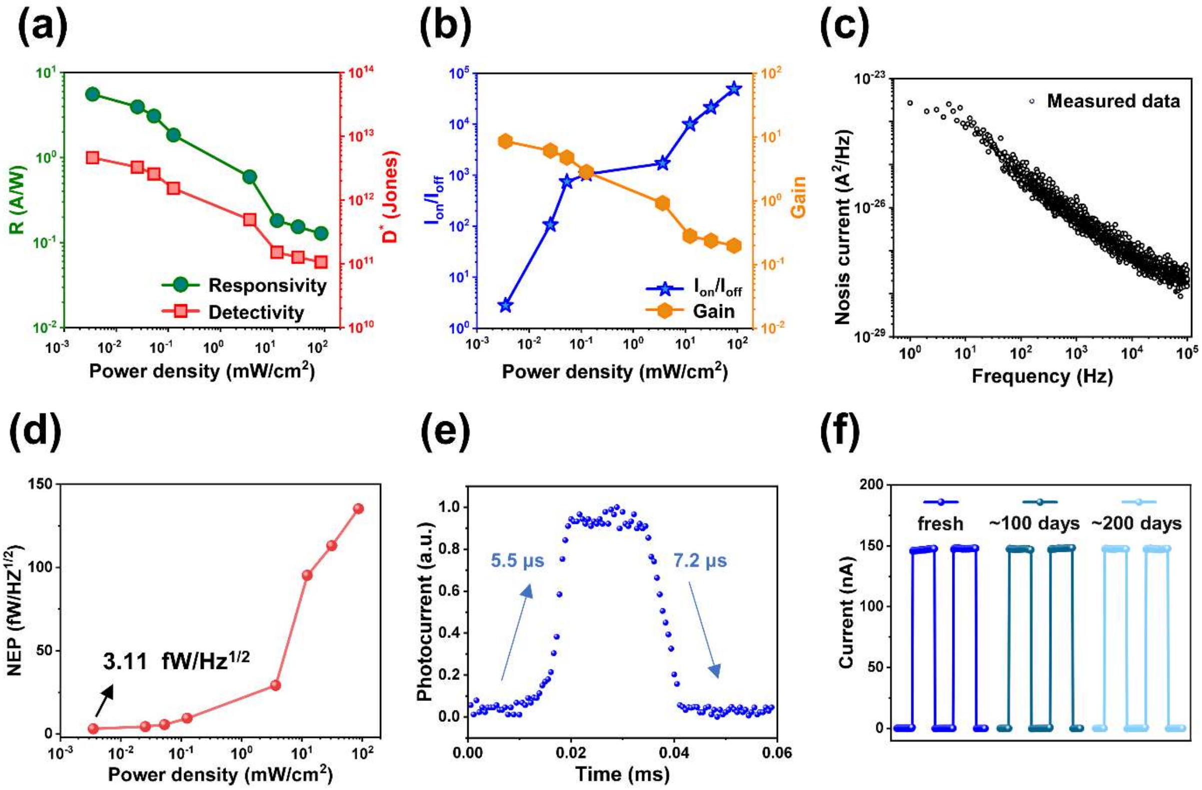

Figure 3. Photoresponse parameters of the Gr/Si photodetector under self-powered mode at 808 nm illumination. (a) *R* and D^* of the device as a function of power density. (b) I_{on}/I_{off} and *Gain* of the device as a function of power density. (c) Frequency-dependent noise current spectral density in the dark state. (d) Equivalent noise power. (e) Response time of the device. (f) Stability of the device after long-term storage.

Leveraging the excellent response speed and photodetection sensitivity of the Gr/Si device, we further explored its feasibility for imaging applications under 808 nm. **Figure 4a** illustrates the experimental setup based on the single-pixel scanning imaging principle: by moving a metal mask with specific patterns point-by-point in the X-Y plane and simultaneously recording the photocurrent signals corresponding to different positions, a 2D image corresponding to the mask pattern was ultimately reconstructed. **Figure 4b-d** presents the reconstructed results for the patterns "向往" , "美好", and "

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生活" , respectively. All images exhibit clear contours and well-defined boundaries, which fully demonstrates the reliable imaging capability of the Gr/Si device in the 808 nm band and further highlights its potential for practical applications in infrared imaging.

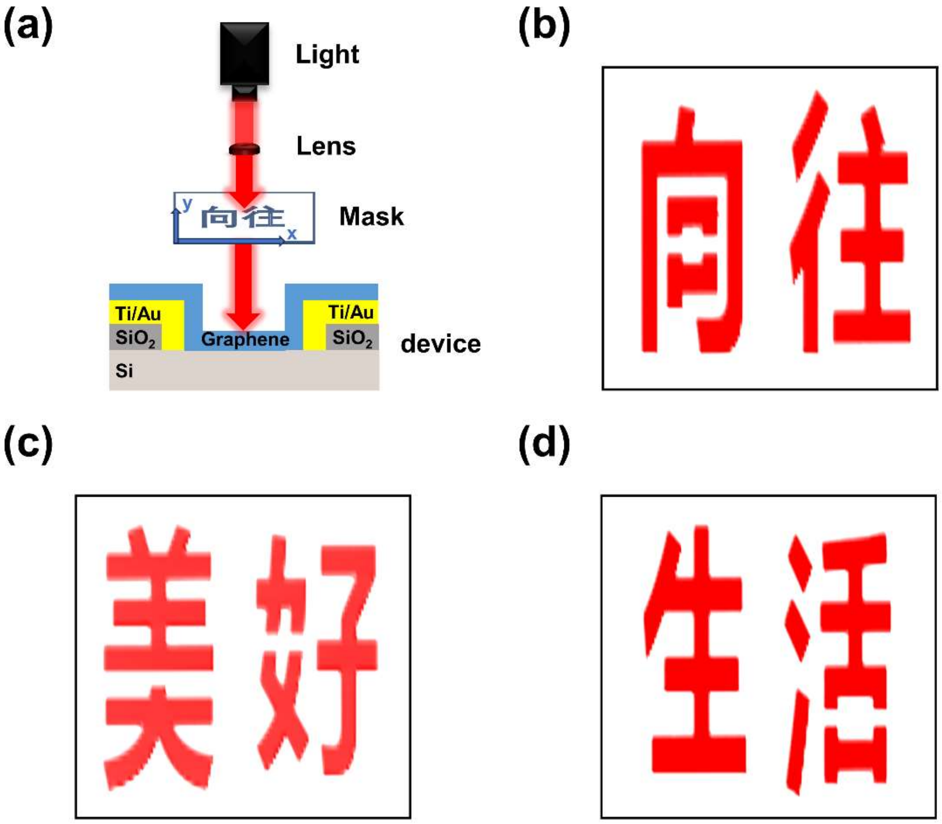

Figure 4. Imaging capability of Gr/Si device. (a) Schematic diagram of the imaging system. (b-d) Imaging results of different patterns characters captured by the device under 808 nm illumination.

3. Conclusion

In summary, this work successfully constructed a vertically configured Gr/Si van der Waals heterojunction photodetector and systematically investigated its self-powered photodetection performance. Experimental results demonstrate that the device exhibits exceptional optoelectronic response characteristics in the near-infrared band: it achieves a R of 5.55 A/W and a D^* of 4.62×10^{12} Jones at 808 nm, along with outstanding I_{on}/I_{off} and *Gain* values of 4.88×10^4 and 8.54, respectively. Furthermore, the device displays a fast transient photoresponse capability, with τ_{rise} and τ_{decay} measured to be 5.5 and 7.2 μs, respectively. Notably, the device maintains highly consistent optoelectronic performance after several hundred days of storage, demonstrating excellent long-term operational stability and reliability. Through interface purification and electrode structure design, this work achieves a systematic enhancement of the near-infrared performance of self-powered Gr/Si heterojunction photodetector, providing a viable technological pathway for the development of high-performance, low-power infrared optoelectronic devices based on 2D materials.

4. Experimental Section

Devices Characterization and Measurements: The morphology and thickness of the graphene films were examined using optical microscopy (Motic, Panthera) and AFM (Bruker, Dimension Icon). The optoelectronic properties of the devices were evaluated using a probe station connected to a source measure unit (Keithley 2636B). Monochromatic lasers (Cnilaser, FSL-FN) with wavelengths of 808 nm and 1064 nm were employed, each having a spot diameter of 3 mm. The incident power for the 808 nm and 1064 nm laser was calibrated using a silicon photodiode (Thorlabs, S120VC).

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Temporal photoresponse characteristics were recorded using a digital oscilloscope (Tektronix, DPO4102B). Noise current spectra were acquired using a semiconductor parameter analyzer (PDA, Fs-pro). For imaging applications, the device was mounted on a printed circuit board, and its characteristics were measured using a custom-built measurement system.

Acknowledgments

The authors gratefully acknowledge the Instrumental Analysis Center of Guangdong University of Technology, Guangzhou, China, for providing experimental facilities and technical support.

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