High-performance flexible photodetectors based on CdTe/MoS₂ heterojunction†

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Flexible photodetectors have attracted escalating attention due to their pivotal role in next-generation wearable optoelectronic devices. This work presents high-performance photodetector devices based on CdTe/MoS₂ heterojunctions, showcasing outstanding photodetecting and distinctive mechanical properties. The MoS₂ film was exfoliated from bulk layered MoS₂ and covered by a sputtered ultrathin CdTe film (~8.4 nm) to form a heterojunction. Benefitting from the photovoltaic effect induced by the built-in electrical field near the high-quality interface, the fabricated CdTe/MoS₂ heterojunction photodetector can operate as a self-powered photodetector without any external bias voltage, especially showing a high photodetectivity of 5.84 × 10¹¹ Jones, remarkable photoresponsivity of 270.3 mA W⁻¹, fast photoresponse with a rise/fall time of ~44.8/134.2 μs and excellent bending durability. These results demonstrate that the CdTe/MoS₂ heterojunctions could have significant potential for future applications in optoelectronic devices.

Introduction

Recently, flexible photodetectors with high performance have attracted significant research attention due to their broad applications in wearable electronics, implantable biomedical devices, electronic sensory skins, and so on.¹⁻³ Presently, optoelectronic devices based on various kinds of functional materials have been developed, but typically require large thicknesses and are fabricated on rigid substrates to achieve sufficient mechanical strength and satisfactory optoelectronic detection performance.⁴⁻⁵ Therefore, a huge challenge still remains for developing flexible ultra-thin photodetector devices with high detection rates on flexible substrates. Two-dimensional (2D) materials exhibit excellent optoelectronic detection performance, huge specific surface area and mechanical stretchability,⁶⁻⁷ thus showing enormous potential applications in flexible optoelectronic sensing devices.

Unfortunately, research on high-performance optoelectronic detectors based on 2D materials remains largely lacking due to significant drawbacks of single two-dimensional films, including slow photoresponse, high dark current, low absorption rate, and reduced detection efficiency.⁸⁻¹⁰ The application of two-dimensional film materials in high-performance flexible photodetector devices is greatly hindered by these shortcomings. To resolve these issues, various kinds of heterojunction devices through the combination of 2D materials with other semiconductors with appropriate energy band structures have been proposed.⁹¹¹ The built-in electric field at the high-quality interface effectively reduces dark noise, accelerates response, and largely improves the photoinduced carrier separation, substantially enhancing the photodetection performance.¹²⁻¹⁶ For instance, a reduced graphene oxide (RGO)-MoS₂/pyramid Si photodetector was reported, exhibiting enhanced light absorption and improved photodetection capability compared to single RGO-MoS₂ due to the internal electric field and increased conductivity.¹⁷ Hence, it is crucial to develop a flexible photodetector device based on heterojunction films to significantly enhance its performance.

Molybdenum disulfide (MoS₂), one of the most competitive two-dimensional materials, is an excellent candidate for flexible photodetection. MoS₂ is composed of one sub-layer of Mo atoms sandwiched between two sub-layers of S atoms, bonded together by interatomic covalent bonds, without surface dangling bonds. Additionally, MoS₂ has an indirect bandgap ranging from 1.2 to 1.9 eV, and the energy band structure can be tuned by adjusting the thickness of the MoS₂ layer.¹⁸ Especially, MoS₂ possesses an impressive high on/off ratio up to 10⁶ and a high carrier mobility of 480 cm² V⁻¹ s⁻¹, which demonstrates its outstanding photodetection performance.⁵¹⁹ Owing to these characteristics, MoS₂ has emerged as one of the most appealing materials for the development of next-
generation high-performance flexible optoelectronic sensor devices.\textsuperscript{19–23}

Up to now, many researchers have focused on MoS\textsubscript{2}-based photodetectors. B. Radisavljevic \textit{et al.} fabricated the monolayer MoS\textsubscript{2} photodetector and a photoresponsivity of 7.5 mA W\textsuperscript{−1} has been achieved under visible light irradiation.\textsuperscript{24} Additionally, the detectable spectral range of MoS\textsubscript{2}-based photodetectors can be extended to the mid-infrared range by incorporating other nanomaterials (such as reduced graphene oxide and silicon pyramid nanostructures)\textsuperscript{17} or by forming heterojunctions with other materials.\textsuperscript{25,26} In 2023, Son \textit{et al.}\textsuperscript{26} reported a high-performance infrared photodetector based on HfS\textsubscript{2}/MoS\textsubscript{2} heterojunction. The device exhibits excellent photodetecting performance due to the promoted separation and transport of photoinduced carriers by the built-in electric field, achieving a high detectivity of 7 \times 10\textsuperscript{13} Jones at 1550 nm. Recently, Wang \textit{et al.} fabricated a MoS\textsubscript{2}/SiO\textsubscript{2} heterojunction photodetector by plasma treatment technique.\textsuperscript{27} Benefiting from the modifying heterointerface, the device exhibits broadband response from 400 nm to 1600 nm, achieving a high responsivity of up to 4.05 \times 10\textsuperscript{4} A W\textsuperscript{−1}. Recently, Deng \textit{et al.}\textsuperscript{28} employed the PBE functional in density functional theory calculations to investigate the optical and electrical characteristics of the CdTe/MoS\textsubscript{2} heterostructure. The results revealed that an internal electric field was formed at the heterojunction interface due to the energy difference between the Te-5p orbitals and the Mo-4d orbitals, enhancing the efficiency of electron–hole separation and light absorption. Therefore, research on the photodetection performance of high-quality CdTe/MoS\textsubscript{2} heterojunctions is of great significance. It holds significant potential for enhancing the absorption coefficient of incident light, photoresponsivity, and photodetectivity of the photodetectors.

In this work, we presented high-performance flexible photodetectors based on CdTe/MoS\textsubscript{2} p–n heterojunctions. Due to the absence of chemical reactions involved in the exfoliation and transfer processes, high-quality MoS\textsubscript{2} films were exfoliated from bulk MoS\textsubscript{2}. Subsequently, the epitaxially sputtered CdTe film was transferred onto the MoS\textsubscript{2} film and a CdTe/MoS\textsubscript{2} heterojunction was fabricated. The fabricated CdTe/MoS\textsubscript{2} heterojunction photodetector exhibits high photoresponsivity (270.3 mA W\textsuperscript{−1}), high photodetectivity (5.84 \times 10\textsuperscript{11} Jones), fast photoresponse (44.8/134.2 μs), and excellent bending durability. This study provides an effective strategy for enhancing the optoelectronic performance of flexible photodetectors and promoting their utilization in next-generation high-performance flexible optoelectronic devices.

Experimental details

\textbf{Synthesis of photodetectors based on CdTe/MoS\textsubscript{2} p–n heterojunction}

The mechanical exfoliation method was used to obtain 2D-MoS\textsubscript{2} films by using scotch tape to peel MoS\textsubscript{2} films from MoS\textsubscript{2} bulk and gradually reduce the number of MoS\textsubscript{2} layers. Then, the 2D-MoS\textsubscript{2} film was transferred to the PDMS substrate, whose upper surface was covered by a layer of Ag electrode, with the help of an accurate transfer platform (Metatest, E1-T). Afterwards, using the magnetron sputtering technique, an ultrathin CdTe film was fabricated on a NaCl single crystal, then the CdTe film was transferred to the upper surface of MoS\textsubscript{2} film with the aid of the polymethyl methacrylate (PMMA) protection, as described in previous work.\textsuperscript{29} Finally, ITO electrodes, which have good light transmission and conductivity, were plated on the upper surface of the ultrathin CdTe film through the magnetron sputtering technique.

\textbf{Characterization of CdTe/MoS\textsubscript{2} photodetectors}

We used the Raman (HORIBA, HR800) and XRD (Bruker D8) to characterize the morphology, crystal structures and chemical composition of the MoS\textsubscript{2} films and CdTe films. The AFM (CSPM 5500) and Hitachi UH4150 spectrophotometer were used to characterize film surface flatness, film thickness, and bandgap of CdTe and MoS\textsubscript{2} films.

\textbf{Optoelectronic and Flexibility measurements}

A home-made optoelectronic measurement system, including a Keithley 2636B source meter and a uniaxial straining apparatus to apply strain to devices, was used to characterize the optoelectronic and flexibility performance of the CdTe/MoS\textsubscript{2} p–n heterojunction device.

\textbf{Results and discussion}

Fig. 1a and b show the surface roughness and film thickness of MoS\textsubscript{2} and CdTe films, characterized by AFM. The MoS\textsubscript{2} film is mechanically exfoliated from the bulk MoS\textsubscript{2} crystal, while the CdTe film is transferred onto the MoS\textsubscript{2} film. As shown in Fig. 1a, the uniform and smooth surface of the MoS\textsubscript{2} film was fabricated due to the layered structure and the acid-free exfoliation process. Fig. 1b exhibits the smooth surface of the CdTe film with a low root-mean-square roughness (RMS) of ∼1.65 nm, indicating high-quality growth. Fig. 1c shows the layered structure of the bulk MoS\textsubscript{2} crystal. Due to its unique layered structure and the absence of dangling bonds between unit layers, MoS\textsubscript{2} can be exfoliated layer by layer to ultrathin layers with a smooth surface, even a single unit layer. As shown in the insets, the thicknesses of the MoS\textsubscript{2} and CdTe thin films can be determined to be ∼71.9 nm and ∼8.35 nm, respectively. XRD analysis further investigated the crystal structure of the CdTe/MoS\textsubscript{2} heterojunction, as shown in Fig. 1d. The peak at 23.8° corresponds to the (111) lattice plane of CdTe films, indicating a zinc blende structure (PDF: No. 15-0770), suggesting a single (111)-oriented growth along the out-of-plane direction. Additionally, the MoS\textsubscript{2} film exhibits multiple diffraction peaks at 14.5°, 29°, 43.5° and 58°, corresponding to the crystal orientations (002), (004), (006) and (008) (PDF: No. 87-2416). Fig. 1e presents the Raman spectrum of MoS\textsubscript{2} film, including E\textsubscript{g} (383.6 cm\textsuperscript{-1}) and A\textsubscript{1g} (408.8 cm\textsuperscript{-1}) vibrations of 2H-MoS\textsubscript{2}. Notably, the wavenumber difference (Δ)
between the $E_{2g}$ and $\Gamma_{8}$ modes is about 25.2 cm$^{-1}$, verifying the few-layer structure.\textsuperscript{30} Raman spectroscopy was performed to characterize the structural and chemical information of the CdTe/MoS$_2$ heterojunction (Fig. 1f). The peaks at 140.1 cm$^{-1}$ (TO) and 162.9 cm$^{-1}$ (LO) are attributed to the Cd–Te bonds, while the presence of Te precipitates is indicated by the peak at 121.9 cm$^{-1}$.\textsuperscript{31}

Fig. 2a depicts the schematic structure of the CdTe/MoS$_2$ heterojunction. The $I$–$V$ curve of the CdTe/MoS$_2$ heterojunction photodetector was measured in dark conditions (Fig. 2b). The device shows obvious rectifying characteristics with a rectification ratio exceeding 46.3, indicating the formation of the junction near the CdTe/MoS$_2$ interface. Under 405 nm laser illumination, $I$–$V$ curves of the CdTe/MoS$_2$ heterojunction showcase the evidently asymmetry, as depicted in Fig. 2c. The asymmetric curve indicates that the fabricated CdTe/MoS$_2$ heterojunction exhibits obvious photoresponse behaviours at varying laser powers from 0.0 to 24.0 mW. The photocurrent increases with increasing laser power, indicating a strong dependence of the photoresponse on laser powers. Due to the built-in electric field near the heterojunction interface, the photodetector device can function without any external bias voltage, demonstrating self-driven operation. This would largely reduce the energy consumption and simplify the circuit design. The time-dependent photoresponse curve was measured under 405 nm laser illumination with different incident laser powers to further investigate photoresponse properties. In Fig. 2d, $I_{on}/I_{off}$ ratios of the device increase from 443.4 (1.3 mW) to $6.74 \times 10^3$ (20.8 mW). From Fig. 2d, typical photoresponse peaks in the photoresponse curve can be observed. The mechanism of these peaks can be explained by the thermoelectric effect.\textsuperscript{32,33} When the laser is suddenly irradiated on the CdTe/MoS$_2$ heterojunction, a transient temperature rise leads to the generation of a transient thermoelectric field at the heterojunction interface with a direction from MoS$_2$ to CdTe. The transient high current peaks can be attributed to the combination of the thermoelectric field current and the photovoltaic current. The temperature gradient gradually disappears with continuous light irradiation, and the current value returns to the steady state photovoltaic current. In addition, the time-dependent photoresponse curves of the device under 520 nm and 980 nm are also measured, as shown in Fig. S1 and S2.\textsuperscript{†} The CdTe/MoS$_2$ heterojunction device exhibits obvious photoresponse to the 520 nm and 980 nm illumination, showing a wide spectral response. Thus, the fabricated heterojunctions would have large potential application in broadband optoelectronic devices. Fig. 2e illustrates the relationship between photocurrent ($I_{ph}$) and laser power. It is observed that the photocurrent gradually increases with increasing incident laser powers. The correlation between photocurrent and incident laser powers is fitted by using the power law of $I_{ph} = A \times P_{in}^\vartheta$ where $\vartheta$ denotes the ideality factor. The $\vartheta$ value, determined to be 0.95, closely approximates 1, suggesting minimal trap states within the CdTe/MoS$_2$ heterojunction. Responsivity ($R_{res}$) and detectivity ($D^*$) are crucial parameters of photodetectors and can be expressed as:

$$R_{res} = \frac{I_{ph}}{P_{in}} \quad (1)$$

$$D^* = \frac{A^2 \cdot R}{(2eI_{d})^2} \quad (2)$$

where the $I_{ph}$, $P_{in}$, $A$ and $I_d$ are the photocurrent, the laser power, the effectively illuminated area and the dark current, respectively. To further analyse the optoelectronic performance of the CdTe/MoS$_2$ photodetector, the responsivity and detectivity at different incident laser powers were calculated and plotted in Fig. 2f. With decreasing laser power, both $R_{res}$ and $D^*$ increase. The values of $R_{res}$ and $D^*$ can reach a maximum of 270.3 mA W$^{-1}$ and $5.84 \times 10^{11}$ Jones at laser power of 0.0739 mW, respectively. In addition, we measured the noise spectrum of CdTe/MoS$_2$ heterojunction, and showed that NEP up to $4.38 \times 10^{-15}$ W (Fig. S3†). Using the NEP, we recalculated the detection rate up to $2.27 \times 10^{10}$ Jones (Fig. S4†). To investigate the response speed, a pulsed light of 405 nm was applied to the CdTe/MoS$_2$ photodetector. Fig. 2g presents the time-dependent photoresponse properties of the device at a fre-
frequency of 1000 Hz. The response time ($\tau_{\text{res}}$) and the recovery time ($\tau_{\text{rec}}$) are determined to be 44.8/134.2 $\mu$s. Furthermore, the photoresponse as a function of modulation frequency was measured with a deduced 3 dB frequency (which corresponds to the cut-off frequency when the current decays to 0.707 times of the initial stable value) exceeding 2 kHz (Fig. S5†). Table 1 compares the performance of the reported flexible and related devices based on two-dimensional materials. Comparatively, the exfoliated CdTe/MoS$_2$ flexible device in this work exhibits high photoresponsivity, high photodetectivity and excellent bending durability, suggesting the considerable potential for next-generation wearable optoelectronic devices.

To further clarify the operational mechanism of this heterojunction, band gaps of ultrathin CdTe and exfoliated MoS$_2$ are investigated in Fig. 3a and b using UV absorption spectroscopy, revealing band gaps of 1.40 eV and 1.64 eV, respectively. Fig. 3c schematically illustrates the energy band structure of the heterojunction to elucidate its operational mechanism. Due to the difference between the Fermi levels, when p-type CdTe and n-type MoS$_2$ come into contact, electrons migrate from the MoS$_2$ layer and accumulate in the CdTe layer through diffusion, whereas holes accumulate in the MoS$_2$ layer in reverse. As a result, energy band bending occurs at the interface, and a type-II heterojunction is formed. An internal electric field ($E_{\text{bi}}$) along the direction from MoS$_2$ to CdTe at the junction is formed. When the heterojunction is irradiated with 405 nm laser, electron–hole pairs are excited and the built-in electric field within the heterojunction facilitates their separation. Therefore, self-driven photodetecting behaviours of the fabricated heterojunction are exhibited. The built-in electric field of the heterojunction drives the separation of electrons

Table 1 Comparison of the flexible and related device performance in recent work

<table>
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<th>Materials</th>
<th>Flexible (yes or no)</th>
<th>$R$ (mA W$^{-1}$)</th>
<th>$D^*$ ($10^{11}$ Jones)</th>
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<td>270.3</td>
<td>5.84</td>
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Fig. 2 (a) The structural schematic of the CdTe/MoS$_2$ heterojunction. The current–voltage ($I$–$V$) curves of the photodetector under (b) dark conditions and (c) different light intensities. (d) The dynamic photoresponse curves under a 405 nm laser with different light intensities at zero external bias voltage. (e) Photocurrent ($I_{\text{ph}}$) versus laser powers ($P_{\text{in}}$). (f) The relationship curve between detectivity and responsivity with respect to laser power. (g) The photodetector’s time-dependent response to light signals at a frequency of 1000 Hz. (h) The rising and falling edges.

Fig. 3 (a) The UV absorption spectrum of ultra-thin CdTe films and (b) exfoliated MoS$_2$ films to investigate the energy gap. (c) Energy bands and the photoexcitation process of the CdTe/MoS$_2$ photodetector.
and holes, while also impeding their recombination.\textsuperscript{38,39} Moreover, the CdTe/MoS\textsubscript{2} heterojunction exhibits high quality with reduced internal defects, leading to enhanced photovoltaic conversion efficiency and consequently a higher detection rate.\textsuperscript{40} Thus, the excellent responsivity, superior detectability and ultrafast response of the heterojunction are attributed to the photovoltaic effects of MoS\textsubscript{2} and CdTe and the excellent CdTe/MoS\textsubscript{2} heterojunction quality.

Fig. 4a presents the bending diagram of flexible CdTe/MoS\textsubscript{2} p-n heterojunction photodetectors. To examine the correlation between photoresponse and bending strain, dynamic photovoltaic response curves of the CdTe/MoS\textsubscript{2} heterojunction photodetector were measured under different bending strain conditions, as depicted in Fig. 4b. Since the thickness of the CdTe and MoS\textsubscript{2} films is negligible compared to the PDMS film, only the thickness of the PDMS film is considered to calculate the bending strain. The bending strain is calculated using the formula $\varepsilon = h/2r$. In this formula, $h$ is the thickness of PDMS film and $r$ is the bending radius. The device is subjected to the maximum bending strain of 2.13%. Fig. 4b illustrates the dynamic response period curves of the device under various strains. The photocurrent exhibits slight changes under folding strains ranging from $-2.13\%$ to 2.13\%, indicating the stable photoresponse characteristics. Fig. 4c shows the relationship between photocurrent and strains. As shown in the figure, the photodetector device shows high stability with a slight variation of $\sim 5\%$. The mechanical stability of the device is assessed through dynamic response curve testing after different strain cycles, as shown in Fig. 4d. After 50, 100, 150, and 200 cycles, the photocurrent decreases by less than 10\%, indicating an excellent mechanical stability.

**Conclusions**

In summary, flexible CdTe/MoS\textsubscript{2} heterojunctions were fabricated, exhibiting a remarkable photovoltaic detection of $5.84 \times 10^{11}$ Jones, a high responsivity of 270.3 mA W\textsuperscript{-1} and a fast response time of 44.8/134.2 $\mu$s. Moreover, CdTe/MoS\textsubscript{2} photodetector shows great mechanical stability with a slight photocurrent variation after 200 periodic strain cycles. These characteristics demonstrate the fabricated CdTe/MoS\textsubscript{2} heterojunctions have enormous potential applications in developing next-generation wearable photoelectronic devices.

**Author contributions**

Lanzhong Hao and Yunjie Liu conceptualised and guided the research. Shuo Yang and Yupeng Wu fabricated CdTe/MoS\textsubscript{2} heterojunctions and conducted structural characterisation, photovoltaic testing and flexible photovoltaic testing of heterojunctions. Shuo Yang prepared the first draft of the paper. Fuhai Guo and Mingcong Zhang provided guidance on sample quality and instrumentation issues that arose during the experiment. Xingru Zhu tested the UV absorption spectra. All authors actively contributed to the discussion.

**Data availability**

The data supporting this article have been included as part of the main article and the ESL.$^{\dagger}$

**Conflicts of interest**

There are no conflicts to declare.

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**References**

5. J. Wang, J. Han, X. Chen and X. Wang, *InfoMat*, 2019, 1, 33–53.