

High-Efficiency Monolayer Molybdenum Ditelluride Light Emitting Diode and Photodetector

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ABSTRACT: Developing a high efficiency and low-cost light source with emission wavelength transparent to silicon is an essential step toward silicon based nanophotonic devices and micro/nano industry platforms. Here we demonstrate a near infrared monolayer MoTe₂ light emitting diode (LED) that emission transparent to silicon. By taking advantage of the quantum tunneling effect, the device has achieved a very high external quantum efficiency (EQE) of 9.5% at 83 K, which is the highest EQE obtained from LED devices fabricated from monolayer TMDs so far. When the device is operated as a photodetector, the MoTe₂ device exhibits a strong photoresponsivity at resonant wavelength 1145 nm. The low dark current of ~5pA and fast response time 5.06 ms are achieved due to suppression of hBN tunneling layer. Our results open a new route for the investigation of novel near infrared silicon integrated optoelectronic devices.

Keywords: Molybdenum Ditelluride, light emitting diode, quantum efficiency

1. INTRODUCTION

Recently, monolayer TMDs have attracted tremendous attention due to their unique properties, including the indirect-to-direct bandgap transition¹⁻², the large exciton and trion binding energy³⁻⁴ and tunable band alignment⁵ in atomically thin layers. Those distinct

properties make them promising active materials for next-generation optoelectronic applications, including excitonic lasers,⁶ photodetectors,⁷ and LEDs.⁸ Currently, much effort has been put to investigate TMD-based LEDs in the visible range. Research progress in the near-infrared to infrared range has been barely reported. However, the infrared light source is usually a key component of on-chip silicon-based optical interconnects and high-speed communication systems. Thus, to explore and fabricate high-efficiency advanced infrared LED light sources becomes a crucial task. Typically, there are two popular architectures for fabricating TMD-based LED devices. One is lateral monolayer devices⁹⁻¹⁰ by using electrostatic doping to form an adjacent p-n junction within the material. The other one is vertical tunneling devices¹¹⁻¹³ that artificially introduce quantum wells (QWs) to engineer the recombination of electrons and holes. EQE is considered to be a critical parameter in LED devices. By using splitting gates, Ross et al. have reported a lateral p-n junction monolayer WSe₂ LED with ~1% efficiency.¹⁰ They also demonstrated that emissions of LED can be tuned between excitons and trions via modulating the injection bias. Compared to the lateral structure, a vertical structure allows higher injection current efficiency via larger contact area, more emission area, and thus higher efficiency. Although a high EQE (~8.4% at 6 K) has been achieved by using multiple QWs,¹⁴ the quantum efficiency for most single QW TMD-based LED is still quite low. Withers et al. have demonstrated a vertical tunneling MoSe₂ LED and a tunneling WSe₂ LED by using boron nitride as tunnel barriers and graphene as contact electrodes.¹³ They reported that the monolayer WSe₂ tunneling LED achieved 5% efficiency at room temperature. Besides, Carmen et al. also successfully demonstrated the vertical tunneling WSe₂ and WS₂ quantum LED devices by taking advantage of boron nitride as tunnel layer.¹² They proposed that those LED devices have single photon behavior. In addition, the emission wavelength of lateral or vertical structure LED devices have been limited within CCD detection range so far and silicon (Si) or silicon dioxide (SiO₂) is used as

host substrates. However, silicon substrate itself has a very strong absorption in CCD detection range. F. Withers et al.¹³ reported that, in a monolayer tungsten diselenide (WSe₂) LED with highly reflective distributed Bragg reflector (DBR) substrates, the EQE reached 5% at room temperature. Up to 30% of the emitted light could be collected by the detector for LEDs based on such DBR substrate compared to only 2% from those with Si/SiO₂ substrates. In order to achieve a high-efficiency infrared light source, a high-quality optical gain material is necessary. Monolayer MoTe₂, a special family member of two-dimensional (2D) TMDs, has an electrical bandgap of ~1.72 eV.^{4, 15} The exciton emission peak from monolayer MoTe₂ is located at ~1.1 eV¹⁵ and is very close to the silicon bandgap, making it nearly transparent for silicon, which is essential for on-chip integrated high-efficiency silicon photonics and optoelectronics. Bilayer MoTe₂ has been successfully demonstrated to fabricate infrared LEDs and photodetectors by applying electrostatic doping to form a lateral adjacent p-n junction¹⁶. However, this electrostatic doping method is more difficult to achieve in monolayer MoTe₂ because of the complicated fabrication process and low electrical excitation tolerance. In this work, we demonstrate the vertical structure monolayer MoTe₂ LED via a solution- and lithography-free transfer process. The total emission area reaches 80 μm². Importantly, we show that our MoTe₂ LED device has an extremely high EQE of around 9.5% at 83K, which is the highest EQE that has been achieved in monolayer TMD LEDs. Moreover, this vertical structure can also be extended to be a photodetector. The response time of our MoTe₂ photodetector has been measured to be ~5.06 ms with an extremely low dark current of ~5 pA, which is comparable to other MoTe₂-based photodetectors.¹⁷ Our results pave the way for the investigation of the next-generation silicon-integrated on-chip infrared optoelectronic devices.

2. EXPERIMENTAL SECTION

2.1. Device fabrication and characterization. The Monolayer MoTe₂ and the few layers hBN were mechanically exfoliated onto the SiO₂/Si substrate. Transfer stacking process was done with a homemade transfer platform (Supporting Note 1). The 100nm thickness gold electrodes were directly patterned in a plain SiO₂/Si substrate by conventional photolithography, metal deposition and lift-off process. The homemade micromanipulator was used to peel off Au electrodes and then transfer them to LED devices.

2.2. Optical characterization. PL, Raman and EL measurements were conducted using a Horiba LabRAM system equipped with a confocal microscope, a charge-coupled device (CCD) Si detector, and a 532 nm diode-pumped solid-state (DPSS) laser as the excitation source. For temperature-dependent (above 83 K) measurements, the sample was placed into a microscope-compatible chamber with a low-temperature controller (using liquid nitrogen as the coolant). The electrical bias for LED was applied using a Keithley 4200 semiconductor analyzer. The spectral response of the photodetector devices was measured using the conventional amplitude modulation technique with a tungsten-halogen lamp as a white illumination source, a mechanical chopper, an Acton SpectraPro 2300i monochromator, a Stanford SR570 low noise current pre-amplifier and a Stanford SR830 DSP lock-in amplifier. The two-dimensional photocurrent mapping was performed with a WITec alpha300S scanning microscopy system.

3. RESULTS AND DISCUSSION

Figure 1a & b show the schematic and optical microscope image of the monolayer MoTe₂ LED. The single tunneling junction is made of stacked graphite, hexagonal boron nitride (hBN) and monolayer MoTe₂ from top to bottom. A monolayer MoTe₂ sample identified by a

phase shift interferometer (PSI) was firstly mechanically exfoliated onto a SiO₂/Si (275 nm thermal oxide on n⁺-doped silicon) substrate and then the sample was stored in vacuum to avoid any oxidation or contamination (Supporting Figure S1). A 6 to 8 layers hBN identified by PSI was also exfoliated onto the SiO₂/Si substrate for subsequent processes (Supporting Figure S2). We used a dry-peel-and-lift van der Waals technique to assemble our devices,¹⁸ and the whole transfer process was solution-free (Supporting Note 1). From bottom to top, MoTe₂ monolayer and thin-layer sample with irregular shape (white dashed line in Figure 1b) was mostly covered by a large piece of thin-layer hBN (blue dashed line in Figure 1b), with graphite (black dashed line in Figure 1b) located on top of monolayer-MoTe₂/hBN heterostructure serving as one electrode. The top thin-layer hBN serves not only as a tunneling layer to realize device function but also as a capping layer to protect the active MoTe₂ layer from contamination to enhance device performance and stability. Figure 1c illustrates the measured Raman spectrum from the monolayer MoTe₂/hBN/graphite overlapping area excited with a 532 nm laser. The characteristic phonon response of the A_{1g} at 172.1 cm⁻¹ and E_{2g} at 235.9 cm⁻¹ is consistent with previously report in monolayer MoTe₂.¹⁵ The small peak B located at 183 cm⁻¹ may be the second order Raman modes of monolayer MoTe₂, as observed in other TMDs.¹⁹⁻²¹ The Raman peak of hBN was observed at around 1366 cm⁻¹, corresponding to the characteristic peak of E_{2g} phonon mode. This extremely low peak intensity indicates that our hBN flake is very thin, which is consistent with the previous report that the peak intensity becomes progressively weaker as hBN layer number decreases.²² The characteristic peaks of graphite were also observed in the high frequency region at 1581 cm⁻¹ (G band) and 2718 cm⁻¹ (2D band).²³ Figure 1d shows typical electroluminescence (EL) and photoluminescence (PL) spectra of our monolayer MoTe₂ LED. By applying a negative bias onto top graphite electrode and grounding monolayer MoTe₂, electrons and holes would tunnel through the hBN layers into the active MoTe₂ monolayer,

leading to the I-V curve shown in Supporting Figure S5. Strong EL from monolayer MoTe₂ can be obtained at an even higher temperature (83 K) compared to previous reports,¹²⁻¹³ as illustrated (red) in Figure 1d. In order to understand the nature of the EL, the PL spectrum (blue) at 83 K from the same location is also presented. The measured PL spectrum exhibits two clear peaks with central wavelengths at ~1036 nm (1.197 eV) and ~1051 nm (1.179 eV) and they are noted as exciton and trion emission from monolayer MoTe₂, which matches well with the previous observation.⁴ In the PL spectrum, one broad peak located at 1121.6 nm (1.1 eV) can also be observed and is assigned to be the PL emission from n⁺-doped silicon (Supporting Figure S4). The center peak of the EL spectrum is located at 1034.6 nm (1.198 eV) with 29 meV full-width-at-half-maximum (FWHM). The similar peak positions between the EL and PL spectra and the extremely small FWHM for the EL peak indicate that the EL emission is exciton dominant. Less trion contributions in EL spectrum compared with PL spectrum reflects that the initial doping of our monolayer MoTe₂ is slightly n-type after LED device fabrication (Supporting Note 5). The injected electrons and holes would form excitons before the radiative recombination, reflecting the large exciton binding energy at high temperature due to the strong Coulomb interaction in monolayer MoTe₂.

Figure 2a shows EL spectra of monolayer MoTe₂ LED with increasing injection current. A single EL peak located at 1034.6 nm can be observed from all spectra under different injection currents, indicating that our monolayer MoTe₂ remained in high quality after complicated device fabrication process. Figure 2b is a spatial mapping of the EL peak intensity from the MoTe₂ LED device at 83 K. Monolayer MoTe₂, few-layer hBN, and graphite region is outlined by white, blue, and black dashed line, respectively. The EL mapping shows uniform and strong emission from the entire monolayer MoTe₂ region, suggesting that the injected current evenly flows through the monolayer region. The total

illuminating area reached around $80 \mu\text{m}^2$, which is 10 to 20 times larger than that in typical lateral structure LEDs.¹⁰ With an illuminating area of $80 \mu\text{m}^2$, the current density of measured highest EL spectra in Figure 2a is only $75.9 \text{ nA}/\mu\text{m}^2$. The plot of the integrated EL intensity as a function of injection current shows two different slopes with an apparent threshold at $5.05 \mu\text{A}$ (Figure 2c red curve). The integrated EL intensity increases slowly below the threshold, and it increases dramatically above the threshold. This current threshold may result from the direct tunneling (DT) and Fowler-Nordheim tunneling (FNT) transition (discussed later).²⁴ Furthermore, the strong EL emission under the small drive current suggests that our device has a very high EQE. Here the EQE is defined as $EQE = eN_{ph}/\eta I$, where e is the electron charge, N_{ph} is the number of photons detected by the detector, η is the system collection efficiency (Supporting Figure S3), and I is the current passing through the device active area. Figure 2c shows the EQE as the function of the injection current (blue curve). Similar to the trend of integrated EL intensity, the EQE curve also exhibits the doubled-slope feature with the transition at $5.05 \mu\text{A}$. We believe that the double-sloped EQE and integrated EL intensity are related to the transition of DT and FNT effect. Apart from the definition of EQE above, the EQE can also be expressed as follows: $EQE = \eta_{Radiative} \cdot \eta_{Injection} \cdot \eta_{Extraction}$. Here, $\eta_{Radiative}$ is the radiative recombination efficiency, $\eta_{Injection}$ is the current injection efficiency and is defined as the fraction of current injected into the QW that recombines radiatively and non-radiatively with respect to the injected and escaped current, and $\eta_{Extraction}$ is the extraction efficiency and is defined as the ratio of the generated photon that can be extracted from a device to total photons from a QW.²⁵ In our experiment, all EL spectra were collected with the same system, and thus $\eta_{Extraction}$ was the same for all spectra. The EQE in this case is determined by $\eta_{Radiative}$ and $\eta_{Injection}$. The radiative recombination efficiency is typically a constant, and this value is mostly determined by

material itself. Therefore, the overall EQE is related to current injection efficiency which can be expressed as:

$$\eta_{Injection} = \frac{I_{QW_total}}{I_{QW_total} + I_{Barrier_total}}$$

where I_{QW_total} is total recombination current in the MoTe₂ layer and $I_{Barrier_total}$ is total recombination current in the hBN barrier area. The total injection current (I_{total}) is the sum of both I_{QW_total} and $I_{Barrier_total}$.

Before further discussion, it is necessary to note that our EL measurement was conducted in the small current regime, which is far away from the quantum efficiency saturation or EQE suppression (efficiency droop) regime. Therefore, the escaping current from the QW can be considered to be a small constant. The device operated when electrons were injected into the MoTe₂ layer after tunneling through the few-layer hBN barrier. The DT process typically happens at low voltage region, while the FNT process dominating at high voltage region (Supporting Figure S6). Under small voltage (DT process), electrons in graphite need to tunnel a trapezoidal hBN barrier into the QW (Supporting Figure S6a). No matter how high the graphite Fermi level rises, the barrier thickness will never change and the current loss in the barrier area ($I_{Barrier_total}$) is proportional to I_{total} , which results in a low and uniform current injection efficiency. However, the hBN barrier shape changes from trapezoid to triangle when the tunneling process becomes FNT (Supporting Figure S6b) at higher biases. In triangular barrier scenario, the barrier thickness becomes narrower as the graphite Fermi level rises, which causes easier tunneling of electrons into the QW and significantly decreased current loss in the barrier area ($I_{Barrier_total}$), leading to higher and increasing current injection efficiency, as shown in Figure 2c.

To further demonstrate the high EQE of our device, we have compared the EQE of our monolayer MoTe₂ LED with previously reported monolayer TMD-based LEDs, as presented in Figure 2d.^{8, 10, 13-14} For vertical structure LED devices (ref 13 and 14), they were both measured in the small injection current regime where the EQE monotonically increases with the injection current and the EQE was recorded at their highest injection current. In our measurement, the highest injection current was much smaller than those in reported devices. The EQE of our device at highest injection current (75.9 nA/μm²) was measured to be 9.5%, which is nearly twice of what was measured in a monolayer WSe₂ LED with an injection current of 9.4 μA/μm².¹³ Taking into account the 124 times smaller injection current, the total EQE enhancement reaches a maximum of ~236 times. Such high quantum efficiency in our device arises from two aspects: 1) the delicate device structure, ultra clean interface of devices, dry membrane transfer and photolithography-free electrodes pattern technique; 2) low substrate absorption at the emission wavelength of MoTe₂. Considering the vulnerability of the active monolayer MoTe₂, our device structure was designed to be an inversion of the common vertical structure.¹² Our PL studies showed that bottom-placed MoTe₂ layer successfully avoided surface contamination and sample degradation (Supporting Figure S7). Besides, a dry and lithography-free method was used to transfer membranes and to pattern electrodes (Supporting Note 1).²⁶⁻²⁷ Therefore, our device was assembled under a totally dry environment and no molecules were introduced from any organic solution, which can be seen in our clear PL spectra without any defect related peaks. Compared to other visible TMD-based LEDs, our monolayer MoTe₂ LED has an emission wavelength at ~1035 nm that is very close to the Si bandgap. Silicon has a weak absorption coefficient at 1.1 eV of ~ 1.5 cm⁻¹,²⁸⁻²⁹ therefore the emitted light from MoTe₂ monolayer is nearly transparent to silicon. By introducing a back-reflecting mirror or other light trapping structure on the back of the substrate, the device EQE can be further improved.

To further understand the tunneling effect of our LED device, we measured its electrical properties. The $I_{ds}-V_{ds}$ curve of the device under different back-gate voltages and corresponding analysed band diagrams are illustrated in Figure 3. Here we discuss 6 different states labeled in Figure 3a & b. The corresponding band diagrams are presented in Figure 3c-3f. The whole device consists of three parts in the band diagram, including Schottky barrier (SB), MoTe₂ active layer, and hBN barrier. Firstly, the device is under 20 V back-gate voltage ($V_{bg} = 20$ V), leading to a relatively large SB between graphite and MoTe₂ (State 1 and 2). A positive bias ($V_{ds} = 40$ V) applied to another graphite electrode lowers the graphite Fermi level (E_F) below the valence band (E_V) of gated MoTe₂, which induces holes to tunnel through the hBN barrier into MoTe₂ layer (State 1, as illustrated in Figure 3c). On the contrary, a negative bias ($V_{ds} = -40$ V) applied to graphite electrode will raise its E_F above the conduction band (E_C) of gated MoTe₂, resulting in electrons tunneling into MoTe₂ layer (State 2, as illustrated in Figure 3d). Meanwhile, holes in the other side graphite cannot be injected into MoTe₂ monolayer because of the large energy barrier for hole. In the above two scenarios, there is no radiative recombination due to lack of electrons or holes in monolayer MoTe₂. Subsequently, state 3 and 4 show that when the device is under -20 V back-gate voltage ($V_{bg} = -20$ V), the conduction and valence band of MoTe₂ bend upwards, which narrows the SB width. If the E_F of graphite closed to hBN side is lowered below E_V of the gated MoTe₂, holes can also tunnel into MoTe₂, similar to the situation in Figure 3c, but with a larger current because of the smaller SB (State 3, as illustrated in Figure 3e). In state 4 (Figure 3f), when our device is under -20 V back-gate voltage ($V_{bg} = -20$ V) and graphite closed to hBN side is under a large negative bias ($V_{ds} = -40$ V), electrons in this graphite can tunnel into the MoTe₂ monolayer after raising the E_F . In the meantime, holes are also able to tunnel through the SB into MoTe₂ monolayer. And then electrons and holes recombine

radiatively leading to a great of photon emissions. The state 5 and state 6 illustrate the scenario before our device emitting light, which has been explained in supporting note 3. By modulating the Fermi level of the graphite, we can manipulate the injection of electrons and holes in this type of vertical structure device and thereby realize device control.

As the initial doping of the monolayer MoTe₂ is quite small,⁴ the doping level of MoTe₂ could significantly change when it is under different gates.³⁰ Therefore, it is worth discussing the gate effect on behaviours of the device. Firstly, the source and drain current in Figure 3a and 3b is compared at a given V_{ds} equals to 40 V. The source and drain current for V_{bg} at -20 V is larger than the V_{bg} at 20 V. When V_{bg} is set at 20 V, the channel type in MoTe₂ is n-type and electrons are the majority of charge carriers. In this case, holes injected from tunneling through hBN could not generate large current. However, the channel type in MoTe₂ switches to p-type when V_{bg} is set to -20 V. The holes become majority carriers leading to larger current. Conversely, the current for V_{bg} at -20 V is smaller than the V_{bg} at 20 V when the given V_{ds} is at -40 V. In this scenario, electrons are injected through hBN. The channel type changes from p-type to n-type when V_{bg} increasing from -20 V to 20 V. Our results are consistent with previous report.³⁰

The above electrical and light emitting studies demonstrate excellent optoelectronic performance in our vertical tunneling structure. However, the photodetection property based on MoTe₂ material and such tunneling structure are barely reported. Here we have further extended our device into photodetector and conducted some initial characterizations of photo response properties. Figure 4a up-panel shows the optical microscope image of our monolayer MoTe₂ photodetector that has the same configuration as our LED device. The monolayer MoTe₂ is fully covered by a few-layer hBN flake. The corresponding photocurrent

mapping at 5 V bias ($V_{ds} = 5$ V) with a 532-nm laser excitation (9 nW) is presented in Figure 4a bottom panel, with the graphite and MoTe₂ region outlined by black and white dashed line, respectively. The photocurrent mapping clearly indicates that photo-response comes from the monolayer MoTe₂ close to the edge of the graphite. Under 5 V bias, the E_F of graphite is lowered and thus only some of holes can tunnel into the MoTe₂ monolayer. This small amount of tunneling holes contributes dark current in this case, as shown in Figure 4b, left panel. By inserting the hBN tunneling layer, the dark current can be highly suppressed. With light illumination, the minority electron population in the conduction band of MoTe₂ is significantly enhanced and can tunnel into graphite to generate light current (Figure 4b, right panel). However, photoexcited electrons beyond the carrier diffusion length will recombine radiatively or non-radiatively before arriving the graphite electrode, which causes the photo-response only showing near the edge of the graphite.

The spectral photoresponsivity of our device is measured and illustrated in Figure 4c. This wavelength-dependent photoresponsivity is largely attributed to light absorption by MoTe₂ monolayer. The photoresponsivity is negligible for photons with wavelength longer than 1180 nm (energy smaller than 1.05 eV), corresponding to the exciton bandgap of monolayer MoTe₂. Apart from MoTe₂ exciton photoresponsivity peak, we also observed that the photoresponsivity reached its maximum increase rate at 690 nm, indicating the monolayer MoTe₂ band edge, which is consistent with previous report⁴. Remarkably, another strong resonate peak located at 450 nm can also be observed in the spectrum. We attribute this peak to C peak originated from the regions of parallel bands near the Γ point, which rises from the band nesting effect (Supporting Note 2).⁴ We also measured the response time of our device, as displayed in Figure 4f. The rise and fall time in our device are 5.34 and 5.06 ms, respectively. Such short response time is attributed to the flat hBN surface above the MoTe₂,

which minimizes charge transfer at the hBN/MoTe₂ interface and again, reflects our ultra-clean device fabrication process. Finally, the photo-detectivity, one of the most important parameters in photodetector, indicates the capability of a device to detect weak signal and it can be calculated by using following formula:¹⁷

$$D = \frac{EQE(qA)^{1/2}}{h\nu(2I_{dark})^{1/2}}$$

Where external quantum efficiency $EQE = R(h\nu/e)$, q is the elementary charge, h is Planck constant, $\nu = c/\lambda$, c is the speed of light in vacuum, λ is 1145 nm and I_{dark} is 5×10^{-12} A. The detectivity is calculated to be 2.6×10^9 cm Hz^{1/2}W⁻¹.

4. CONCLUSIONS

In conclusion, we have demonstrated vertical structured high-efficiency monolayer MoTe₂ LED for the first time, and it shows extremely high performance with an EQE of ~9.5% at 83 K. The working principle of this vertical tunneling device has been identified by band diagram study under different situations. Such kind of LED presents a huge potential to be future near-infrared on-chip light sources. And their efficiencies can be further improved by creating multiple QWs¹³ and delicate tuning of the hBN barrier thickness. Furthermore, this hBN encapsulated structure can also be extended to photodetection with strong photoresponsivity and fast response time. Our results open a new route for the investigation of novel infrared optoelectronic devices.

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Competing financial interests

The authors declare that they have no competing financial interests.

Supporting Information Available: See supporting information file.

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FIGURE CAPTIONS

Figure 1 | Architecture of monolayer MoTe₂ LED. **a**, Schematic of our monolayer MoTe₂ LED and electrical connections for EL measurements. **b**, Optical microscope image of the monolayer MoTe₂ LED. The white, blue and black dashed line outline the footprint of MoTe₂, hBN, and graphite, respectively. Monolayer and bilayer MoTe₂ area are marked as 1L and 2L. **c**, Raman spectrum of the MoTe₂/hBN/graphite overlapping area. Inset: Zoom-in raman peak of the MoTe₂ (red curve) and the hBN (blue curve). **d**, Measured PL and EL spectrum from the same location of the monolayer MoTe₂ LED device at 83 K. The injection current for EL emission is 6.07 μ A under back gate voltage at -20 V.

Figure 2 | Strong infrared EL emission at 83 K. **a**, EL spectra from monolayer MoTe₂ under different injection current and -20 V back gate voltage. The spectra are collected from black dot in **b**. **b**, EL mapping image of the MoTe₂ LED device under an injection current of 9.7 μ A and -20 V back gate. The blue, white and black dashed line outlines hBN, MoTe₂, and graphite. Scale bar, 20 μ m. **c**, EL intensity (left) and EQE (right) of monolayer MoTe₂ as a function of the injection current. **d**, Quantum efficiency for different monolayer TMD devices.

Figure 3 | Working principle of the monolayer MoTe₂ LED device. **a**, $I_{ds} - V_{ds}$ curve for the device under various back-gate voltages at room temperature. State 1 to 6 are marked in different locations. **b**, Zoom-in image of the left part of $I_{ds} - V_{ds}$ curve in **a**. **c**, Band diagram of the device operating at state 1 ($V_{bg} = 20V$, $V_{ds} = 40V$) in **a**. **d**, Band diagram of the device operating in state 2 ($V_{bg} = 20V$, $V_{ds} = -40V$) in **a**. **e**, Band diagram of the device operating in state 3 ($V_{bg} = -20V$, $V_{ds} = 40V$) in **a**. **f**, Band diagram of the device operating in state 4 ($V_{bg} = -20V$, $V_{ds} = -40V$) in **a**.

Figure 4 | Photo-response of monolayer MoTe₂ photodetector. **a**, up panel: Optical microscope image of the monolayer MoTe₂ photodetector. White and black dashed line

outlines MoTe₂ and graphite. Few-layer hBN is located between graphite and MoTe₂. Bottom panel: Photocurrent mapping image of the same area. The image was acquired at $V_{ds} = 5$ V and $V_{bg} = 0$ V under 532-nm excitation laser (9 nW). **b**, Band diagram of the monolayer MoTe₂ photodetector. Left and right side shows the device working without and with light illumination, respectively. **c**, Photo-responsivity as function of wavelength under 10 nW white light, with $V_{ds} = 5$ V and $V_{bg} = 0$ V. **d**, Temporal photocurrent of the monolayer MoTe₂ photodetector. Incident light: 10 nW white light, $V_{ds} = 5$ V, $V_{bg} = 0$ V. The rise time (5.34 ms) is defined as the time of the photocurrent increases to 90% of the ON-state current. The fall time (5.06 ms) is defined as the time for the photocurrent decreases to 10% of the ON-state current.

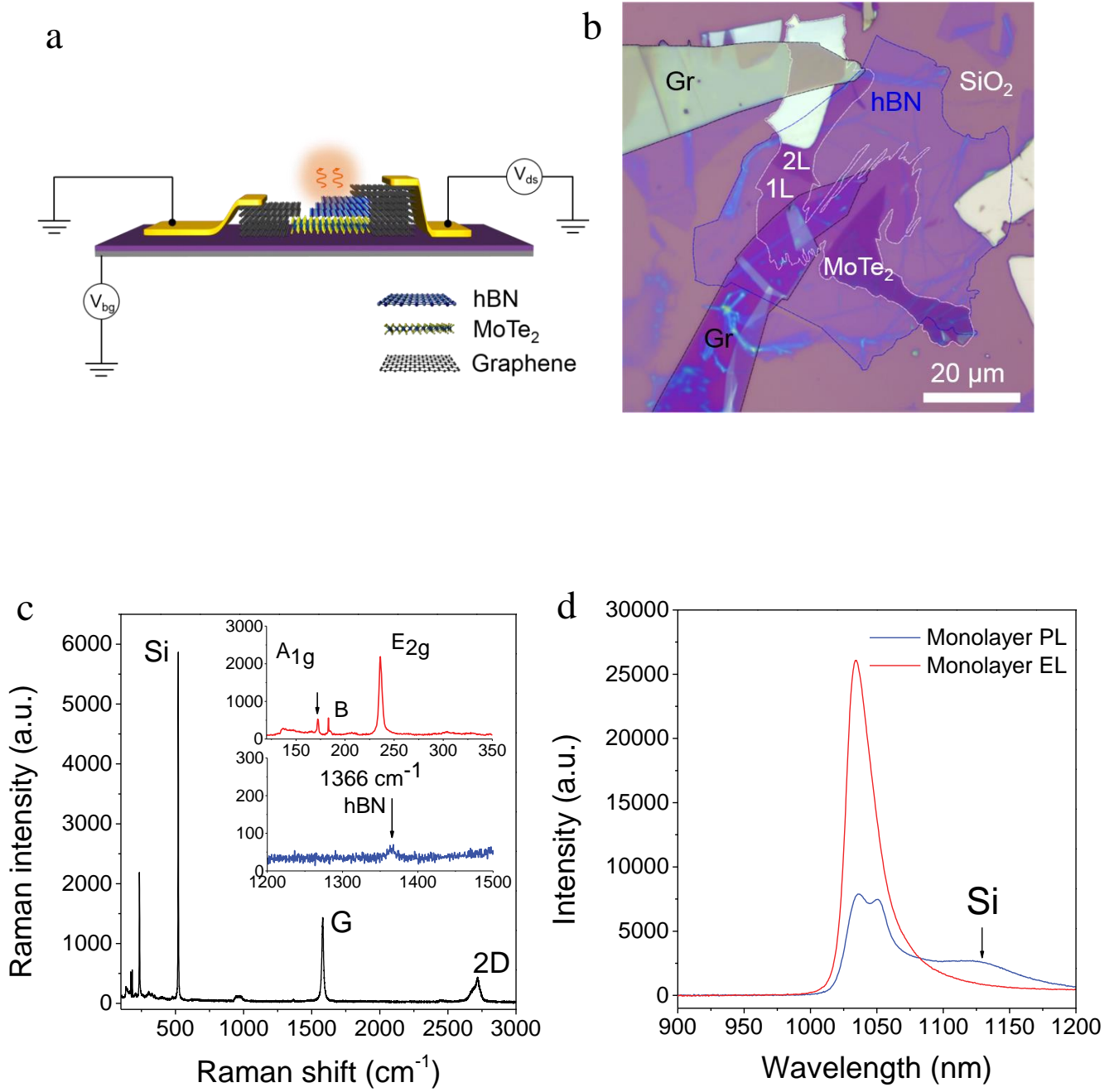


Figure 1

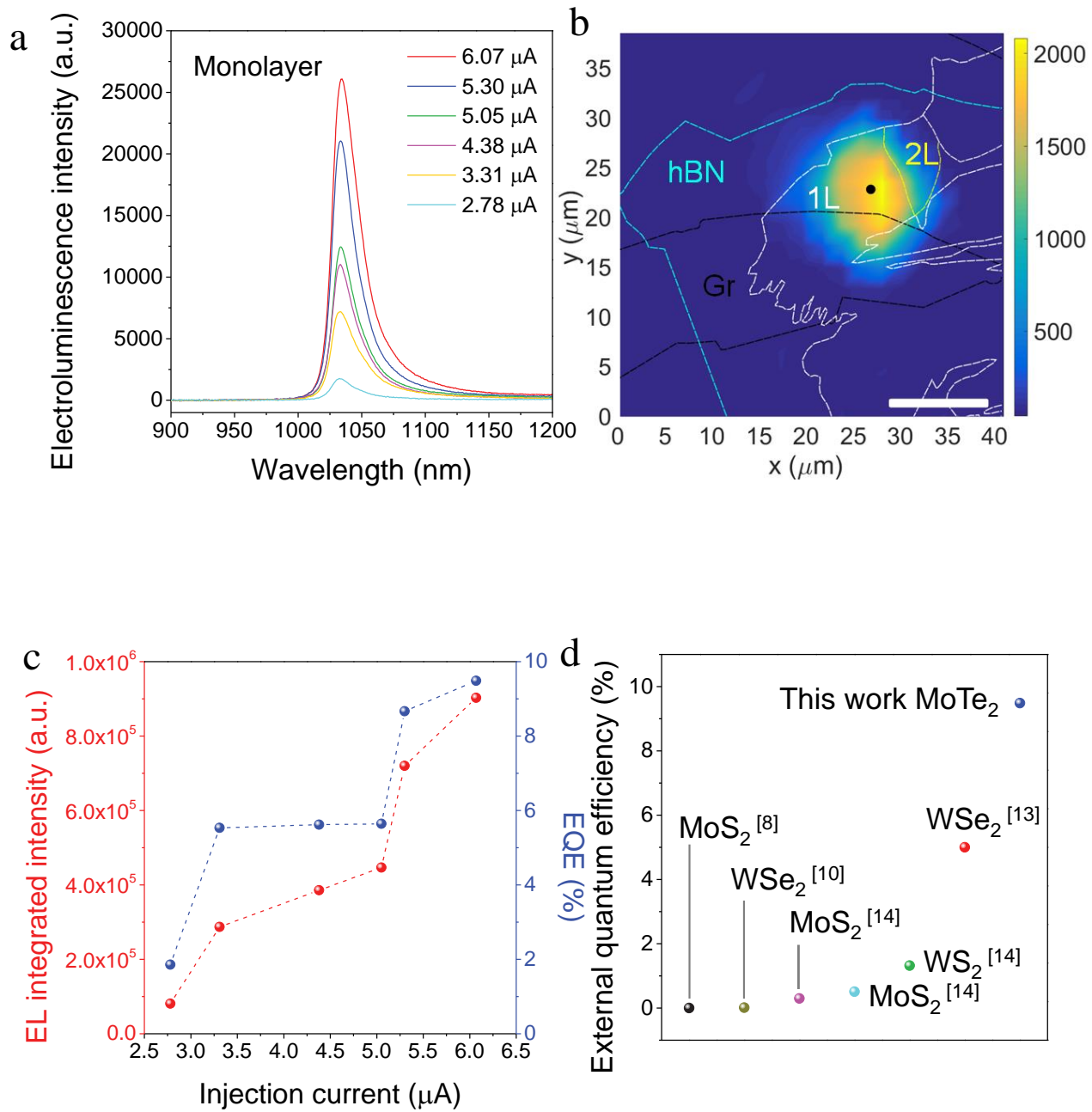


Figure 2

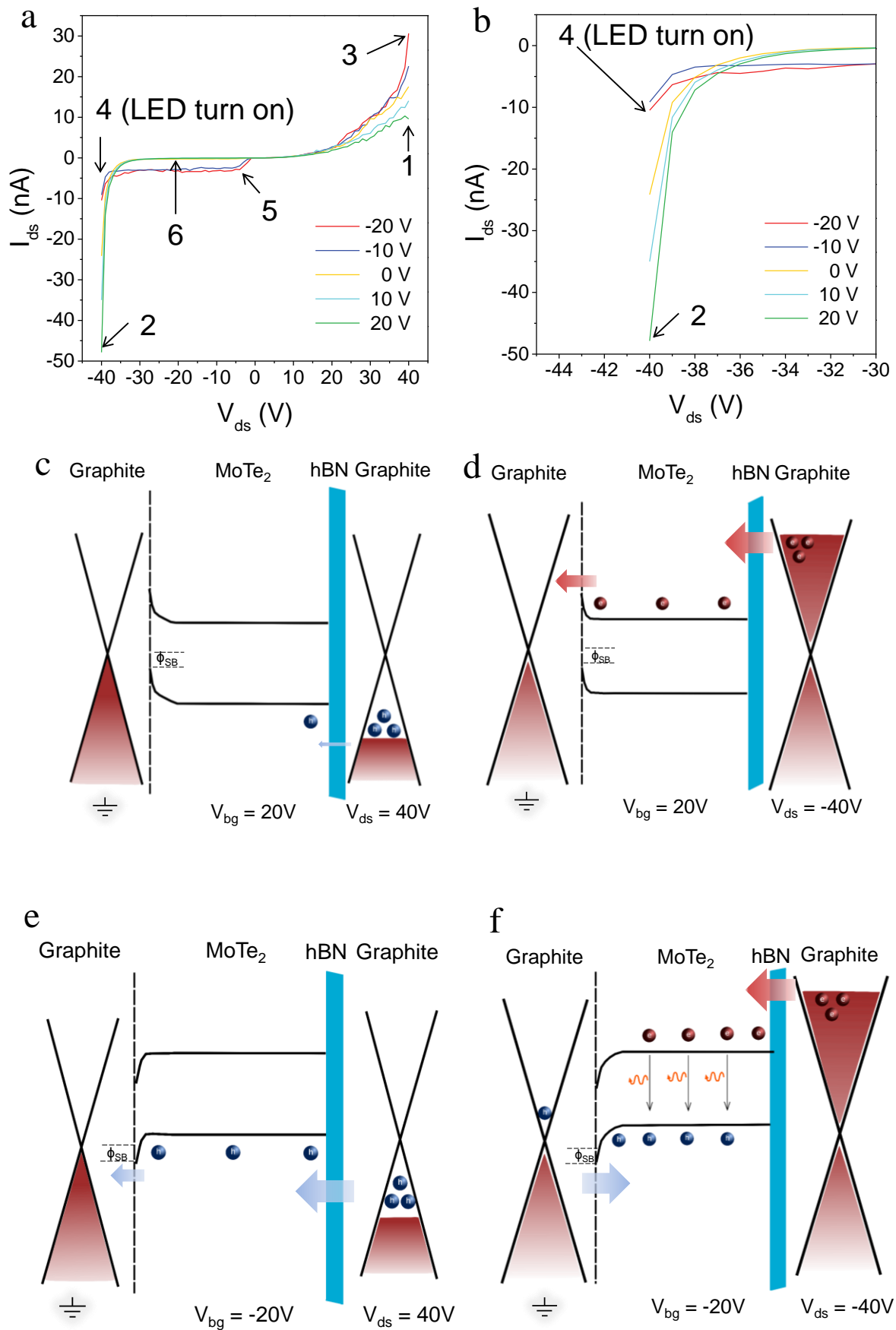


Figure 3

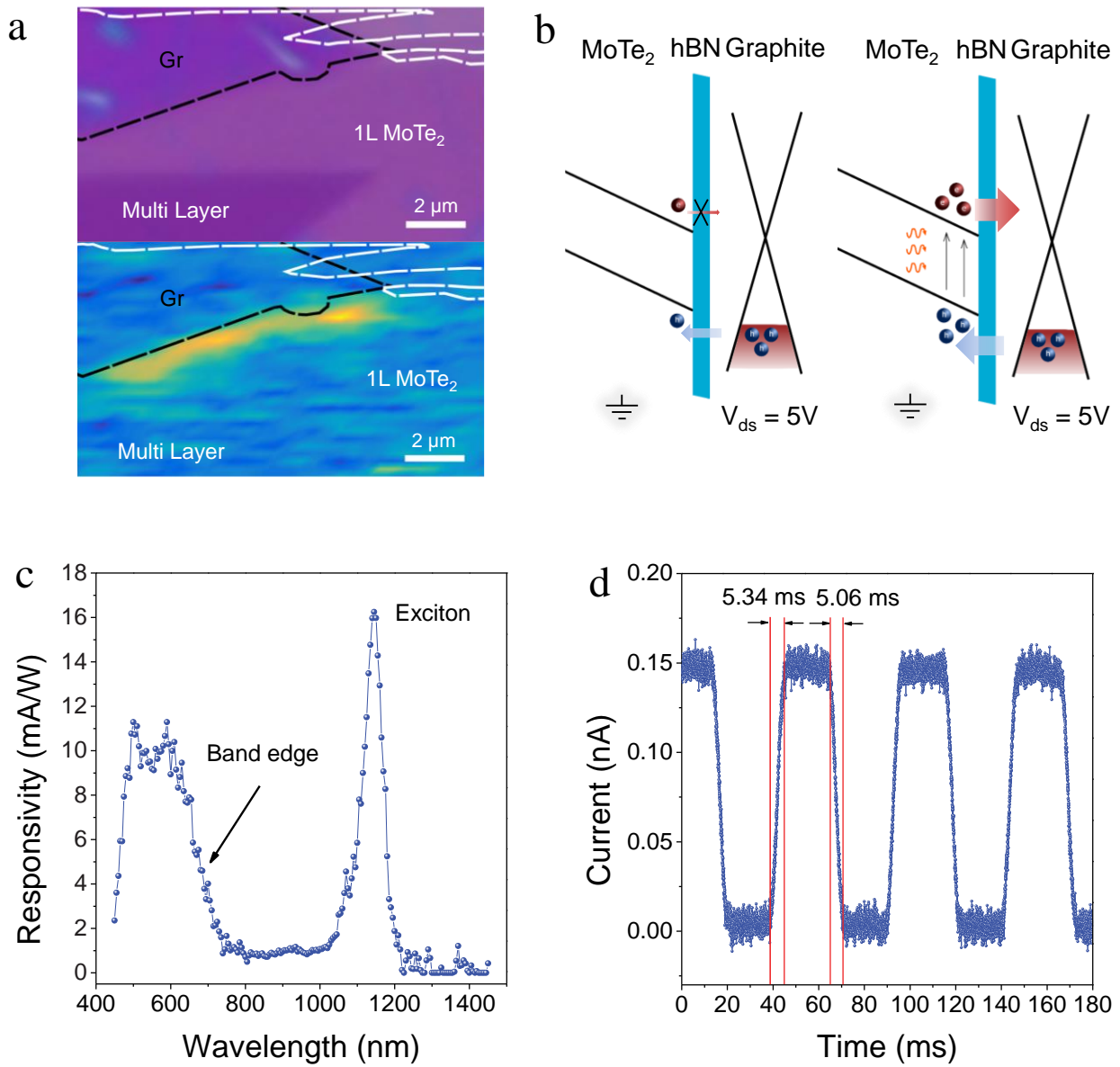


Figure 4

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TOC graphic

