Light-Driven WSe$_2$-ZnO Junction Field-Effect Transistors for High-Performance Photodetection

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Assembling nanomaterials into hybrid structures provides a promising and flexible route to reach ultrahigh responsivity by introducing a trap-assisted gain ($G$) mechanism. However, the high-gain photodetectors benefitting from long carrier lifetime often possess slow response time ($t$) due to the inherent $G$–t tradeoff. Here, a light-driven junction field-effect transistor (LJFET), consisting of an n-type ZnO belt as the channel material and a p-type WSe$_2$ nanosheet as a photoactive gate material, to break the $G$–t tradeoff through decoupling the gain from carrier lifetime is reported. The photoactive gate material WSe$_2$ under illumination enables a conductive path for externally applied voltage, which modulates the depletion region within the ZnO channel efficiently. The gain and response time are separately determined by the field effect modulation and the switching speed of LJFET. As a result, a high responsivity of $4.83 \times 10^3$ A W$^{-1}$ with a gain of $\approx 10^4$ and a rapid response time of $\approx 10$ $\mu$s are obtained simultaneously. The LJFET architecture offers a new approach to realize high-gain and fast-response photodetectors without the $G$–t tradeoff.

Nanomaterials have shown great potential as photosensitive elements thanks to their unique properties, such as broadband response and fast response time.[1–9] After years of study on the photoresponse of single-material-based devices, researchers have begun to combine different nanomaterials into hybrid structures in order to enhance the performance of photodetectors.[10–17] Especially, employing sensitizers to decorate the transport channels has been widely adopted to achieve an ultrahigh gain based on photogating effect.[18–26] However, one obstacle in such devices is that the long lifetime of photoexcited carriers captured in sensitizers would result in slow response, which is a common problem with trap-assisted gain mechanism. Though great efforts have been made to use various materials or device structures to regulate the...
gain–response time (G–t) tradeoff, the key to solving this issue is how to decouple the gain from carrier lifetime. In addition, strongly light-absorbing materials, such as colloidal quantum dots (CQDs), have been widely used in high-gain phototransistors (2D material-CQDs phototransistors and thin-film semiconducting material-CQDs phototransistors) in order to enhance the photogate. The performance of these devices largely depends on the light absorption capacity of sensitizer. This restricts the versatility in realizing high-gain photodetectors in other materials.

In this work, a light-driven junction field-effect transistor (LJFET) is proposed to overcome the G–t tradeoff to achieve high-performance photodetection. The LJFET configuration contains an n-type ZnO belt as the channel material on which is a p-type WSe2 nanosheet as a photoactive top-gate material. As it shows below, the WSe2 works as a light-driven switch to control the application of top-gate voltage on the ZnO channel. As a result, the channel conductance is modulated by externally applied top-gate voltage rather than photogate or photovoltage induced by sensitizers, and the response time is determined by the switching speed of LJFET. The experimental results exhibit a high responsivity of 4.83 × 10^3 A W\(^{-1}\) with a gain of ≈10^4 and a fast response time of ≈10 \(\mu\)s at the same time. Moreover, because the bandgap of WSe2 nanosheet is ≈1.2 eV, the photoresponse covers a spectral range from the visible to near-infrared.

**Figure 1.** Structure and operating mechanism of WSe\(_2\)-ZnO LJFET. a) A schematic illustration of the device in the dark. The p-type WSe\(_2\) nanosheet as the gate material is transferred onto the n-type ZnO channel and side top-gate electrodes (TG). b) Cross section of the device. The high-resistance WSe\(_2\) prevents the negative \(V_{tg}\) from being applied to the WSe\(_2\)-ZnO junction. c,d) The device operates with light illumination. The incident light excites the photocarriers in WSe\(_2\), decreasing the resistance of WSe\(_2\) nanosheet. A conductive path for \(V_{tg}\) is formed between side top-gate electrode and overlapped region. The negative \(V_{tg}\) can be applied to the WSe\(_2\)-ZnO junction. e) Simulated electron density distribution of the device in the dark and under 637 nm illumination. The negative \(V_{tg}\) (−1 V) as a reverse bias can be applied to the junction through the photoexcited WSe\(_2\) nanosheet, leading to an enlarged depletion region within the ZnO channel. f) Electron density along the dashed line in (e). The electron density decreases dramatically under illumination. g,h) The optical picture of the device and the corresponding spatial photocurrent map using a focused 520 nm laser with a power of 5 \(\mu\)W. The device was measured at \(V_{ds} = 1\) V, \(V_{tg} = −0.1\) V and \(V_{bg} = 0\) V. Scale bar, 3 \(\mu\)m. i,j) Photocurrent line trace along the white dashed arrow in the inset. The blue dashed lines indicate the effective photosensitive area.
The depth of depletion region within ZnO channel is hard to be affected (Figure 1b). Under light illumination, when the photon energy is chosen between the bandgap of ZnO (≈3.3 eV)\(^3\,3^{3,34}\) and that of WSe\(_2\) (≈1.2 eV), only photocarriers in WSe\(_2\) are excited (Figure 1c). The reduced resistance of WSe\(_2\) enables a conductive path for the negative \(V_{tg}\) that reversely biases the junction. The enlarged depletion region within ZnO leads to a dramatic increase in the channel resistance (Figure 1d). As discussed below, the positive \(V_{tg}\) as a forward bias will shrink the depletion region, leading to a decrease in the channel resistance. Figure 1e,f presents the simulated electron density distribution of LJFET. A large decrease in electron density of ZnO channel can be observed with illumination. It is worth noting that the illumination also induces a photovoltage at the junction due to the photovoltaic effect (same as the open-circuit voltage of a solar cell) which shrinks the depletion region, leading to an increased current in the channel. These devices need strongly light-absorbing material as the sensitizer to produce a significant photovoltage.

LJFET (this work)

\[
G = \frac{N_d}{N_p} = \frac{\Delta n_{ds} / e}{P / h \nu} = \frac{\Delta n_{ds} \times h \nu}{e \nu \tau}
\]

\(\Delta n_{ds}\) is the change of \(n_{ds}\) induced by \(V_{tg}\)

The photoactive top-gate material as a light-driven switch controls the externally applied top-gate voltage \(V_{tg}\) to modulate the channel conductance. The gain is determined by the modulation of \(V_{tg}\), and the response time is determined by the switching speed of LJFET. This device provides an efficient way to break the \(G\)-\(\tau\) tradeoff. Furthermore, the property of strong light absorption for sensitizers is not necessary.

The photovoltage that arises at the heterojunction between the photoactive material and the conductive channel generates a positive bias (like the open-circuit voltage of a solar cell) which shrinks the depletion region, leading to an increased current in the channel. These devices face a tradeoff between the gain and the response time.

The photoactive top-gate material as a light-driven switch controls the externally applied top-gate voltage \(V_{tg}\) (not photogate or photovoltage) to alter the channel conductance \((\Delta n_{ds})\). The gain is determined by the modulation of \(V_{tg}\), and the response time is determined by the switching speed of LJFET. This device provides an efficient way to break the \(G\)-\(\tau\) tradeoff. Furthermore, the property of strong light absorption for sensitizers is not necessary.
photovoltage) to alter the channel conductance. The gain is determined by the modulation of $V_{tg}$ and the response time is determined by the switching speed of LJFET. This architecture is effective in breaking the G–t tradeoff. Moreover, the property of strong light absorption for sensitizers is not necessary.

To investigate the effect of $V_{tg}$ on photoresponse, transfer characteristics of LJFET under dark and light conditions with $V_{tg}$ modulation were studied. It can be seen from Figure 2a that there is a positive (negative) shift of threshold voltage ($V_{th}$) under negative (positive) $V_{tg}$ modulation even without light illumination (indicated by the black arrow). In our device, WSe$_2$ nanosheet plays the role of a large resistance to weaken the $V_{tg}$ effect on the ZnO channel, but it cannot totally block $V_{tg}$ because it is not entirely insulated. A small fraction of negative (positive) $V_{tg}$ can act on the WSe$_2$-ZnO junction in the dark, inducing a relatively wide (narrow) depletion region. Under light excitation, photocarriers are generated in WSe$_2$ nanosheet. The decreased resistance of top-gate material enables a conductive path for $V_{tg}$, which modulates the channel conductance more efficiently. Because the source-drain voltage applied to the two ends of ZnO channel was set at 1 V (source electrode is connected to the ground), the value of electrical potential at the overlapped region of ZnO channel is between 0 and 1 V. Therefore, when $V_{tg} = 1$ V (Figure 2b), the WSe$_2$-ZnO junction is forward biased. The depletion region in ZnO shrinks, leading to an increased current. A small negative shift of $V_{th}$ was observed. In contrast, when $V_{tg} = 0$ V (Figure 2c), the WSe$_2$-ZnO junction is slightly reverse biased. With the increase of light power, the depth of depletion region increases. A small positive shift of $V_{th}$ was detected. When $V_{tg} = -1$ V (relatively large reverse bias, Figure 2d), the depletion region becomes wider, resulting in a significant decrease in current and a large positive shift of $V_{th}$.

Figure 3a shows the $I_{ds}$–$V_{tg}$ curves under dark and light conditions at $V_{bg} = 15$ V, and the top-gate leakage current $I_{tg}$ is given in Figure 3b. It can be seen that $I_{ds}$ basically remains constant (6.6–6.1 mA) and $I_{tg}$ is close to zero ($10^{-11}$–$10^{-13}$ A) with $V_{tg}$ modulation in the dark. Upon light illumination, there is a positive net photocurrent at $V_{tg}$ from 2 V to 0.6 V and a negative net photocurrent at $V_{tg}$ from 0.6 to $-2$ V (Figure 3a). Accordingly, the polarity of $I_{tg}$ flips at $V_{tg} = 0.7$ V (Figure 3b) which indicates that the electrons flow into and out of the top-gate electrode when $V_{tg} > 0.7$ V and $V_{tg} < 0.7$ V, respectively. Here, a positive $V_{bg}$ was applied to LJFET to enhance the electron density in ZnO and also keep WSe$_2$ depleted of holes (high resistance), in order to achieve light-induced rectifying junction (see Figure S4 and the relevant discussion, Supporting Information). Figure 3c–f shows the energy band diagrams of the device with illumination at different $V_{tg}$. When $V_{tg} > 0.7$ V, the junction is forward biased (Figure 3c). The electrons from ZnO flow into WSe$_2$, contributing to the positive $I_{tg}$. Meanwhile, the depletion region in ZnO shrinks, resulting in a high $I_{ds}$. When $V_{tg} = 0.7$ V, the external applied voltage difference across the junction is equal to the photovoltage (Figure 3d). No electrons pass through the junction, resulting in a zero $I_{tg}$. At the same time, due to that the photovoltaic effect induces a relatively narrow depletion region in ZnO, $I_{ds}$ is somewhat higher than that measured in the dark. With $V_{tg}$ decreases to 0.6 V, the Fermi level of ZnO is equal to that of WSe$_2$ (Figure 3e). The band alignment returns to the original state (Figure S5).
Supporting Information). So, \( I_{ds} \) is equal to that measured in the dark. Additionally, the photoexcited electrons in WSe\(_2\) flow into ZnO, contributing to the negative \( I_{tg} \). When \( V_{tg} < 0.6 \) V, the junction is reverse biased (Figure 3f). The depletion region in ZnO becomes wider to pinch off the channel, resulting in a low \( I_{ds} \). In our device, \( I_{ds} \) is not more than 2 nA with illumination. The light can only change a small portion of the resistance of WSe\(_2\). Because the magnitude and polarity of photocurrent are tunable via field-effect modulation, a very high responsivity can be achieved with appropriate \( V_{tg} \) and \( V_{bg} \).

The \( I_{ds}–V_{ds} \) curves with variable light power intensity at \( V_{tg} = -1 \) V and \( V_{bg} = 15 \) V have been shown in Figure 4a. The illumination causes a distinct decrease in \( I_{ds} \), as marked by the dotted arrow, and a net photocurrent as high as 6.6 \( \mu \)A is obtained at \( V_{ds} = 1 \) V and 367.5 mW cm\(^{-2}\). Accordingly, Figure S6 (Supporting Information) shows the \( I_{ds}–V_{ds} \) and \( I_{ds}–V_{bg} \) curves of a bare WSe\(_2\) transistor by applying the voltage to the two side top-gate electrodes underneath the WSe\(_2\) nanosheet (see Figure 1g). With a power intensity of 367.5 mW cm\(^{-2}\), the anomalous photocurrent reaches a maximum of 6.6 \( \mu \)A, and the WSe\(_2\) transistor only shows a photocurrent about 2 nA at \( V_{ds} = 1 \) V. Although the illumination induces a small increase of the photocurrent in WSe\(_2\), the small change in the resistance of WSe\(_2\) arouses a remarkable field-effect modulation in LJFET. Figure S7 (Supporting Information) shows the simulated electron density distribution of LJFET with illumination. The electron density of ZnO channel decreases with an increase of power intensity. Figure S8 (Supporting Information) presents the photoresponse properties of WSe\(_2\)-ZnO PVFET. A positive photocurrent of \( \approx 0.25 \) \( \mu \)A can be obtained. In this PVFET, photovoltage is not large enough to generate a high photocurrent compared to that in LJFET. This supports the simulation results.

In our device, ZnO with a bandgap of \( \approx 3.3 \) eV is sensitive only to ultraviolet radiation (Figure S9, Supporting Information). Therefore, the WSe\(_2\) nanosheet with a bandgap of \( \approx 1.2 \) eV indicates a broadband photoresponse from the visible to near-infrared range. Figure S10 (Supporting Information) presents the \( I_{ds}–V_{ds} \) curves with 405 and 940 nm light illumination. Both illumination wavelengths caused a distinct decrease in \( I_{ds} \). The responsivities as a function of the light power for different wavelengths are summarized in Figure 4b. The responsivities as high as \( 4.83 \times 10^3 \), \( 1.84 \times 10^3 \) and \( 4.82 \times 10^2 \) A W\(^{-1}\) are obtained for illumination with 405, 637, and 940 nm light, respectively. The higher responsivity with higher photon energy can be attributed to the more efficient excitation of photo carriers in WSe\(_2\). Moreover, the spectral responsivity of the device has been shown in Figure 4c. In the visible region, the responsivity is as high as \( 4.83 \times 10^3 \) A W\(^{-1}\). As the wavelength increases to near infrared, the responsivity decreases to \( 4.82 \times 10^2 \) A W\(^{-1}\). Clearly, the cut-off wavelength is determined by the bandgap of WSe\(_2\) nanosheet. The gain for this LJFET is defined as the number of charges collected by the source-drain electrodes due to the excitation by one photon and given by \( G = \Delta I_{ds} \times \hbar \nu/e \) [48] (parameters have been defined in Table 1). Assuming that...
light incident on the effective photosensitive area is absorbed completely, a gain as high as $1.48 \times 10^4$ is obtained.

Response time is a key parameter that determines the capability of a photodetector to follow a fast-varying optical signal. As shown in Figure 4d, the anomalous photoresponse exhibits highly stable and reproducible characteristics with an $I_{	ext{off}}/I_{	ext{on}}$ ratio of 100 under light modulation. Figure 4e gives the temporal response in a single modulation cycle. The rise edge, defined as the time necessary for a current increase from 10% $I_{\text{peak}}$ to 90% $I_{\text{peak}}$ as fast as 10 $\mu$s, indicating a rapid carrier recombination in WSe$_2$. The fall edge consists of a fast component for a current decrease from 90% $I_{\text{peak}}$ to 35% $I_{\text{peak}} (=10 \mu$s) followed by a slow component from 35% $I_{\text{peak}}$ to 10% $I_{\text{peak}} (=20 \mu$s). The former indicates the fast generation of photocarriers in WSe$_2$, and the latter suggests that ZnO channel undergoes a slightly slow process to reach steady state under $V_{bg}$ modulation. Figure S11 (Supporting Information) presents the temporal response with 405 and 940 nm illumination and shows sharp rise and fall edges, proving that this LJFET device, together with the measurement in Figure 4d, possesses a fast and broadband photoresponse.

In order to study the working bandwidth of WSe$_2$-ZnO LJFET, a relative a.c. photoresponse measurement was performed using a modulated optical signal over a broad frequency range from 10 Hz to 250 kHz. It can be seen from Figure 4f that the device presents a broadband frequency response with a 3 dB bandwidth of 90 kHz. A gain-bandwidth product as high as $1.3 \times 10^8$ Hz was obtained. This value is comparable to that of reported high-gain phototransistors. In our work, the high gain-bandwidth product is achieved by decoupling the gain from the carrier lifetime and without the assistance from strongly light-absorbing materials. This value can be further improved by decreasing the defects in photosensitive material, channel material and interface, which are considered as the main factors affecting response time and bandwidth. In addition, the noise current measurement of LJFET was conducted and it was found that flicker noise ($1/f$ noise) dominates at low frequencies and white noise dominates at high frequencies (Figure S12, Supporting Information). According to the values of noise current and responsivity, a detectivity of $1.56 \times 10^{13}$ cm Hz$^{1/2}$ W$^{-1}$ for 405 nm illumination was obtained. Figure S13 (Supporting Information) gives the temporal response of the other three WSe$_2$-ZnO LJFETs with relatively small dimensions. These devices show fast photoresponse but a little decrease in photocurrent maybe due to the narrow channel width. In our design, although the size and quality of channel materials have impact on the photoresponse of LJFET, the photocurrent can be enhanced by modulating $V_{tg}$ and $V_{bg}$.

To demonstrate that our design is a general approach for high-performance photodetectors, a different gate material, GaSe, was employed to pair with ZnO (Figure 5a). According to the AFM profiles (Figure S14, Supporting Information), the heights of ZnO and GaSe (bandgap of $\approx 2.0$ eV$^{[39]}$ corresponding to 620 nm light) are $\approx 53$ and $\approx 28$ nm, respectively. Figure 5b presents the $I_{ds}$-$V_{bg}$ curves under dark and light conditions. Similar to the WSe$_2$-ZnO LJFET, an obvious shift of the $V_{bg}$ is observed with illumination. With the $V_{bg}$ modulation, positive and negative net photocurrent can also be obtained (Figure 5c). Due to the large resistance of GaSe, only a small fraction of $V_{bg}$ can be applied to the junction even with illumination. So, the voltage...
at the crossing point in Figure 5c is greater than the source-drain bias of 1 V. A net photocurrent of 2.74 µA is obtained at \( V_{ds} = 1 \text{ V} \) and 0.414 mW cm\(^{-2} \) (Figure 5d). Figure S15 (Supporting Information) shows the \( I_{ds}-V_{ds} \) and \( I_{ds}-V_{bg} \) curves of a bare GaSe transistor by applying the voltage to the two side top-gate electrodes underneath the GaSe nanosheet. When the anomalous photocurrent of LJFET reaches its maximum with a power intensity of 0.414 mW cm\(^{-2} \), the photocurrent of the bare GaSe transistor is lower than 30 pA. Interestingly, the GaSe itself does not show good photoresponse, but the GaSe photoexcited in our architecture displays a significant field-effect modulation. Responsivity as high as $1.7 \times 10^4$ A W\(^{-1} \) is obtained (Figure 5e). This result is three orders of magnitude superior to the previously reported responsivity of GaSe based photodetectors\(^{[39,40]} \).

Figure 5f gives a single modulation cycle of temporal response. The rise and fall edges are 165 and 144 µs, respectively, which is slower than that of WSe\(_2\)-ZnO LJFET. In order to study the effect of gate material on response speed of LJFET, Figure S16 (Supporting Information) gives the measurements of temporal response for other GaSe-ZnO LJFETs and Table S1 (Supporting Information) summarizes the response time of reported typical bare GaSe and WSe\(_2\) photodetectors.\(^{[39,40]} \)

In summary, we have developed a novel LJFET for high-efficiency photodetection. In this architecture, the p-type material plays a role of a light-driven switch, controlling the externally applied top-gate voltage to alter the n-type channel conductance. As a result, the gain is determined by the field-effect modulation, and the response time is determined by the switching speed of LJFET. Different from trap-assisted high-gain phototransistors, our devices possess high responsivity and fast response time over a broad spectrum through decoupling the gain from carrier lifetime. The performance can be further improved by appropriate choices of ideal gate materials and transport channels. The simple architecture provides an efficient and reliable way to break the \( G-t \) tradeoff for high-gain photodetectors.

**Experimental Section**

ZnO Growth: ZnO belts used in this work were prepared by a chemical vapor transport method. Equal amounts of ZnO (99.99%, purity) and graphite (99.9%, purity) powders mixed with a 2.5% weight percentage of P\(_2\)O\(_5\) (99.99%, purity) powder as precursors were loaded into a quartz boat that was placed in the center of a tube furnace. A Si/SiO\(_2\) (285 nm) substrate coated with 1 nm thick Au catalyst film was placed on the boat. High-purity Ar (70 sccm, flow rate) and O\(_2\) (15 sccm, flow rate) were used as the carrier gases. The furnace was heated to 1000 °C within 30 min and maintained at that temperature for 10 min. Finally, the samples were cooled to room temperature naturally.

Device Fabrication: First, ZnO belts were transferred mechanically onto p\(^+\)-Si/SiO\(_2\) (285 nm) substrate by direct contact with the sample substrate. The source, drain, and side top-gate electrodes (Cr/Au) were prepared by electron-beam lithography, metallization, and the lift-off
process. Then, the WSe$_2$ or GaSe nanosheet was mechanically exfoliated on a poly-dimethyl siloxane (PDMS) layer. A micromanipulator was used to put the WSe$_2$ or GaSe nanosheet, which is adhered to PDMS, onto the target ZnO channel and the side top-gate electrodes to form the JFET structure using the microscope to locate the position. Finally, the WSe$_2$ or GaSe nanosheet was released from PDMS through heating the substrate.

**Photoresponse Characterization:** Photoresponse measurements of JFET were conducted using a Lake Shore Probe Station with an Agilent B1500 semiconductor parameter analyzer and laser diodes with the wavelengths of 405, 637, and 940 nm. For the temporal photoresponse measurements, an oscilloscope was used to monitor the time dependence of the current. For the scanning photocurrent microscopy measurements, a galvanometer mirror scanning system was used to achieve the laser spot scanning across the device. The device is mounted onto a sample stage, and then illuminated with a focused 520 nm laser using a ×100/NA-0.9 objective. The laser was modulated at a frequency of ~817 Hz with a controller as the reference to a lock-in amplifier from which the photocurrent signal could be extracted. Spectral response measurement was performed using a supercontinuum spectrum laser source combined with a monochromator and Agilent B2902. For the bandwidth measurement, an arbitrary waveform generator was used to drive 405 nm laser, achieving high-frequency light modulation, and a lock-in amplifier was used to acquire photocurrent.

**Device Simulations:** Device simulations were performed using Sentaurus TCAD. The model used in the software was based on drift-diffusion method, where the Poisson's equation and continuity equations for electrons and holes were solved self-consistently by the finite element approach. In order to present the electron density distribution in the cross section of the device more clearly, the device thickness was increased and the channel length was shortened during the simulation. The doping concentrations of p-region and n-region were 10$^{11}$ and 10$^{13}$ cm$^{-3}$, respectively.

**Supporting Information**

Supporting Information is available from the Wiley Online Library or from the author.

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**Conflict of Interest**

The authors declare no conflict of interest.

**Keywords**

gain, junction field-effect transistors, photoresponse, response time, tradeoff

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