Title
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Permalink
https://escholarship.org/uc/item/3ch9g2gs

Journal
Science advances, 4(4)

ISSN
2375-2548

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Publication Date
2018-04-20

DOI
10.1126/sciadv.aap7916

Peer reviewed
Nonvolatile infrared memory in MoS$_2$/PbS van der Waals heterostructures

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Optoelectronic devices for information storage and processing are at the heart of optical communication technology due to their significant applications in optical recording and computing. The infrared radiations of 850, 1310, and 1550 nm with low energy dissipation in optical fibers are typical optical communication wavebands. However, optoelectronic devices that could convert and store the infrared data into electrical signals, thereby enabling optical data communications, have not yet been realized. We report an infrared memory device using MoS$_2$/PbS van der Waals heterostructures, in which the infrared pulse intrigues a persistent resistance state that hardly relaxes within our experimental time scales (more than 10$^4$ s). The device fully retrieves the memory state even after powering off for 3 hours, indicating its potential for nonvolatile storage devices. Furthermore, the device presents a reconfigurable switch of 2000 stable cycles. Supported by a theoretical model with quantitative analysis, we propose that the optical memory and the electrical erasing phenomenon, respectively, originate from the localization of infrared-induced holes in PbS and gate voltage pulse-enhanced tunneling of electrons from MoS$_2$ to PbS. The demonstrated MoS$_2$ heterostructure–based memory devices open up an exciting field for optoelectronic infrared memory and programmable logic devices.

INTRODUCTION

Memory devices constitute the basis of modern electronic information industries (1, 2). However, their operation principles focus on electrical or magnetic manipulation, and the optoelectronic devices (3, 4) for information storage and processing have received far less attention. The optoelectronic storage devices (3–6), which could capture and deposit electromagnetic radiation of matter and function as light-activated logic gates, are of central importance for the development of optical communication, recording, and computing.

The infrared spectra (7) are used as a communication medium for night vision, military communication, object inspection, and medical diagnosis. Specifically, 850, 1310, and 1550 nm are typical optical communication wavebands (8) due to their low energy dissipation in the optical fiber. Therefore, the optoelectronic devices that would convert and store infrared information into electrical signals are highly pursued.

Two-dimensional (2D) materials with gate tunability provide an excellent platform for constructing optoelectronic nonvolatile memory devices. Graphene (9) and monolayer MoS$_2$ (10) have demonstrated a photo-intrigued memory via the persistent photoconductivity (PPC) due to a light-induced metastable resistance state. However, this technology suffers from uncontrollable environmental factors because the materials’ PPC results from charge trapping of disorders or impurities. Recently, the gate voltage–controlled programmable storage of light-induced carriers has been reported in 2D materials (11) and their heterostructures (12). However, the charge storage in these hybrid structures depends on an external negative back gate voltage, which creates the charge trap. Although 2D materials and their mixed van der Waals heterostructures (13, 14) have enabled versatile electronic and optoelectronic functions (15, 16), so far, the study of optical memory using 2D materials is still limited to the visible spectrum. 2D materials, including their heterostructures, cannot simultaneously satisfy efficient infrared absorption and suitable band alignments that can govern the photoexcited carriers. It remains a big challenge to produce optical memory devices operating in the wavebands of infrared radiation (0.76 to 3.0 μm) (17).

Herein, we exploit an infrared memory device using few-layer MoS$_2$/PbS heterostructures with the back gate (V$_{bg}$) (Fig. 1A). The device shows nonvolatile features, in which an infrared pulse intrigues a persistent resistance, and presents a reconfigurable switch of 2000 stable cycles. We demonstrate a physical model using simulations and quantitative analysis that explains the mechanism of the optical memory and the electrical erasing behavior and that proposes potential applications of our device in the optoelectronic memory and programmable logic.

RESULTS

Device structure and operation principle

The few-layer MoS$_2$ flakes were mechanically exfoliated from MoS$_2$ bulk crystals and transferred to SiO$_2$ (280 nm)/n$^+$-Si substrates. Then, infrared-sensitive PbS nanoplates were grown on top of few-layer MoS$_2$ flakes by chemical vapor deposition. The crystallinity quality and chemical composition were examined by a high-resolution transmission electron microscope (HRTEM) with selected-area electron diffraction (SAED) and x-ray photoelectron spectroscopy (XPS), respectively. The HRTEM image (fig. S1) shows distinct crystal fringes with a lattice distance of 0.29 nm in (200) planes. The clear square SAED pattern reveals that PbS nanoplates are of cubic symmetry. The element ratio of Mo to S (~1.0:2.1) is estimated from the XPS spectra area ratio of Mo 4$d$ to S 2$p$, which is very close to the chemical stoichiometry of MoS$_2$. We also obtain an almost perfect element ratio of Pb to S (1.1 to 1.0) in PbS nanoplates from the XPS spectra area ratio of Pb 4$f$ to S 2$p$.

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The carrier transport channel of MoS2 was connected to a Ti (10 nm)/ Au (40 nm) source and drain electrodes. To clarify the optical memory properties, we measured five devices labeled as nos. 1 to 5. All five devices presented similar physical behaviors of optoelectronic transports, optical memory, and electrical erasing, except some difference of memory performance. The main text data were based on the experimental results from device no. 1 unless specified. Figure 1B shows the schematic of band alignment at the interface of MoS2-PbS heterostructure. Because of the build-in electrical field, the PbS energy band (18) bends upward, whereas that of MoS2 (19) bends downward, which creates the holes trap below the valence band of PbS near the interface.

The infrared (808, 1340, 1550, and 1940 nm) illumination-induced electrons in PbS nanolayers are injected into the transport channel of MoS2. There are a few possible mechanisms for electron injection over the barrier from PbS to MoS2. First, the energy scales of 808 nm (1.53 eV), 1340 nm (0.9 eV), and 1540 nm (0.81 eV) are larger than the bandgap of PbS (0.42 eV) and higher than the barrier height (~0.76 eV). The injection of electrons into MoS2 is possible because of photoexcitation of electrons from the valence band or free electrons in the conduction band (20). The photon-enhanced thermionic emission (21) can also induce the carrier injection from the conduction band of PbS to MoS2.

For 1940-nm (0.6 eV) illumination, because its energy scale is smaller than the barrier height, the photo-generated electrons possibly inject into MoS2 by photon-enhanced thermionic emission or the photothermal effect (20). However, infrared-excited holes are localized in PbS due to charge traps, which modulates the conductivity of MoS2 via electrostatic interaction (the photogate effect).

**Optoelectronic transport**

We first investigated the optoelectronic transport in the devices. Figure 1C shows the transfer characteristic curves ($I_{sd}$ versus $V_{g}$) under infrared illumination (808 nm) with various light power densities ($P$). With a low power density ($P \leq 28.2 \mu W \text{ cm}^{-2}$), the photocurrent $I_{ph}$, defined as the change of $I_{sd}$ due to light excitation, varies from positive to negative as $V_g$ decreases from 50 to -40 V (Fig. 1D). Unless otherwise stated, all the measurements were carried out at 80 K with the bias voltage of $V_{sd} = 2$ V in a high-vacuum (10$^{-6}$ torr) chamber of four-probe station. By contrast, at a high power density ($P \geq 0.87 \mu W \text{ cm}^{-2}$), $I_{ph}$ changes from negative to positive with decreasing $V_g$ (Fig. S2D). Control experiments (fig. S3) show that pure few-layer MoS2 does not respond to 808-nm laser pulses, until the laser power density increases to 0.25 mW cm$^{-2}$, and is completely insensitive to 1940-nm laser pulses. This is consistent with the band structure of MoS2 that the direct optical transition occurs at ~680 nm (22). For a fair comparison, the few-layer MoS2 was treated by the similar conditions as the few-layer MoS2 used in the heterostructure.

The photoconductivity of MoS2-PbS heterostructures arises from the injection of infrared-induced electrons in PbS to MoS2.

We now analyze the physical process of carrier injection into MoS2 at a low power density. The field effect mobility ($\mu$) of the device is ~147 cm$^2$ V$^{-1}$ s$^{-1}$, which is independent of $P$ (fig. S2F). Thus, the photocurrent $I_{ph}$ solely depends on the total change of carrier density $\Delta n$ in MoS2. $\Delta n$ is the sum of the change in photo-injected ($\Delta n_{photo}$) carriers and back gate voltage ($V_g$)–accumulated carriers ($\Delta n_{gate}$). $\Delta n$ is expressed as $\Delta n = \eta P t / V_{Mos2} \nu e_0 e_T \Delta V_g / T e$ (see note S1), where $\eta$ describes the photoelectric conversion efficiency determined by the absorption coefficient of PbS and injection efficiency of infrared-excited electrons from PbS to MoS2, $t$ represents the duration of infrared illumination, $h$ denotes the Plank constant, $\nu$ is the infrared frequency, $\Delta V_g = V_g - V_T$, $V_T$ is the threshold voltage of transfer characteristic curves (Fig. 1C), $e_0$ and $e_T$ are the vacuum permittivity and relative permittivity of SiO$_2$, respectively, $T$ is the thickness of MoS2, $V_{Mos2}$ is the volume of the MoS2 nanosheet, $d$ is the thickness of SiO$_2$, and $e$ is the elementary charge. The first term of $\Delta n$ describes $\Delta n_{photo}$ by photo-injected electrons from PbS to MoS2, and the second term displays $\Delta n_{gate}$ which is hole-dominant when $\Delta V_g < 0$ and electron-dominant in the case of $\Delta V_g > 0$. As shown in Fig. 1E, $\Delta n$ is positive when $\Delta V_g > 0$ because both $\Delta n_{photo}$ and $\Delta n_{gate}$ are electron-dominated.

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When $\Delta V_g$ moves toward negative values, $\Delta n$ becomes negative because the net injections of carriers change from electrons to holes. This is consistent with the sign change of photocurrents from positive to negative with decreasing $V_g$ (Fig. 1D). In Fig. 1E, $\Delta n > 0$ and $\Delta \mu < 0$, respectively, indicate that electrons and holes dominate the photocurrent.

In contrast to the low $P$, at a high $P$ of 0.87 and 26.4 mW cm$^{-2}$, the mobility decreases to 140.8 and 131.8 cm$^2$ V$^{-1}$ s$^{-1}$, respectively, leading to a downward shift of $I_{sd}$-$V_g$ curves. Consequently, we observe a negative-to-positive transition of photoresponse as $V_g$ drops (Fig. S2D). As presented in fig. S2E, the $V_T$ gradually decreases from $-21.8$ to $-38.0$ V as $P$ increases from 3.6 to 26.4 mW cm$^{-2}$, implying a larger injection of photo-induced electrons into MoS$_2$ with increasing $P$. The $\mu$ decreases at a high $P$, which can be attributed to the increased Coulomb scattering in MoS$_2$ due to positively charged PbS nanoplates (23, 24).

**Reconfigurable optical memory**

With the injection of photo-induced electrons into MoS$_2$, the infrared-generated holes are localized at traps (Fig. 1B), behaving as the positive gate voltage. This positive photogate effect generates an interesting physical effect of the PPC as shown in Fig. 2A. The device is applied by the infrared pulses (808 nm) with a duration of 5 s and $P$ of 0.55 mW cm$^{-2}$. As the laser pulse switches on, the $I_{sd}$ sharply increases to a finite value ($I_{sd}^m$). Even if the laser pulse switches off, $I_{sd}^m$ hardly relaxes within our measurement duration of 1500 s. The exponential fitting of $\exp(-t/\tau_I)$ leads to the lifetime $\tau_I = 5125$ s of localized holes in the MoS$_2$/PbS heterostructure, which is two orders of magnitude larger than that of localized carriers in pure MoS$_2$ ($\tau_I = 17$ s) (Fig. 2B). The PPC can be removed by $V_g = 40$ V with a duration of 100 ms (Fig. 2C). The above process is highly repeatable at various $V_g$. The photocurrent is positive at $-10$ and 0 V but negative at 10 and 20 V, which is consistent with the photoresponse under 808-nm infrared illumination with a high power density.

**Mechanism of infrared memory**

We now discuss the mechanism of infrared pulse-intrigued memory and $V_g$ pulse-induced erasing. Figure 3 (A to C) displays the time evolution of carrier density distribution in the system, time-dependent magnitude of laser pulses and $V_g$ pulses, and time evolution of the carrier density change $\Delta n$ in MoS$_2$, respectively. At $t = t_0$, when a laser pulse is applied (Fig. 3B), the infrared-excited holes (black pocket in Fig. 3A) are localized in the charge traps of PbS nanoplates with a potential barrier $\Delta E_v = 0.48$ eV (Fig. 4A). The $\Delta n$ in MoS$_2$ instantly raises because of the injection of photo-induced electrons (red pocket in Fig. 3A) from PbS to MoS$_2$ (see $\Delta n_{ph}$ in Fig. 1B). When switching off the laser pulse at $t = t_1$, an interface barrier ($\Phi_B$) prevents the reversed diffusion of electrons from MoS$_2$ to PbS (Fig. 4A). The localized holes cannot be recombined and, hence, induce electrons in MoS$_2$ via the photogate field effect.

At $t = t_2$, a positive $V_g$ pulse instantaneously increases the electron density due to the back gate capacitance effect (Fig. 4C). Thus, we see an immediate rise of photocurrent when $V_g$ pulse is applied as shown by the red dashed circle in Fig. 2C. Our dynamics analysis (see note S2) points out that back gate voltage pulse increases the numbers of transferred electrons ($\Delta n_t$) from MoS$_2$ to PbS (Fig. 4B). The simulation simultaneously considers the quantum tunneling and thermionic emission. We find that electron transferring from MoS$_2$ to PbS ($\Delta n_t$) is far larger than that from PbS to MoS$_2$ ($\Delta n_t$) (fig. S11). In addition, $\Delta n_t$ is dominated by quantum tunneling. The localized holes in PbS are eventually recombined by tunneling electrons from MoS$_2$ due to the downward shift of the conduction band of MoS$_2$, which eliminates the optical memory effect.

To verify the proposed mechanism, we conducted a set of $V_g$ pulse-induced erasing in the heterostructure with writing by 1940-nm pulses. Figure 5A shows the optical memory and electrical erasing effects at various $V_g$ pulses from device no. 3. The laser pulse intriges an increase of photocurrents in MoS$_2$. As mentioned above, the trapped holes in PbS behave as a positive voltage (photogate), which induces electrons

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**Fig. 2.** PPC and rewrtable memory. (A and B) Time evolution of $I_{sd}$ in MoS$_2$-PbS heterostructure and pure MoS$_2$, respectively. The blue dashed line labels the source-drain current under a radiation of laser pulse ($I_{sd}^m$). (C) Writing and erasing of a memory using infrared laser pulses and gate voltage pulses, respectively. A gate voltage pulse of 40 V with a duration of 100 ms is applied to reset the system. The infrared pulse power density is 0.55 mW cm$^{-2}$ with a duration of 5 s. The red dashed circle indicates an instant increase of source-drain current when the gate voltage pulse is applied. a.u., arbitrary units.

**Fig. 3.** Physical principle of infrared memory and $V_g$ pulse erasing. (A) Schematic illustration of time evolution of carrier distribution in MoS$_2$-PbS heterostructure. (B) Magnitude of infrared laser pulses and $V_g$ pulses as a function of time. The laser pulse and $V_g$ pulse switch on at $t_0$ and $t_1$, respectively. (C) Change of carrier density $\Delta n$ versus time in MoS$_2$. The photogate-accumulated electron density $\Delta n_{ph}$ in MoS$_2$ is estimated to be $2.4 \times 10^{14}$ cm$^{-3}$ between $t_1$ and $t_2$ in device no. 3.
in MoS2. The photogate-accumulated electron density \( \Delta n_{\text{photo}} \) in MoS2 is highly stable and maintains the memory state. The inset of Fig. 4C shows a single cycle of laser pulse writing and \( V_g \) pulse erasing. The photogate-induced increase of \( I_{\text{sd}} \) is labeled by \( \Delta I_p \). The photogate-accumulated \( \Delta n_{\text{photo}} \) is estimated to be \( 2.4 \times 10^{24} \text{ cm}^{-3} \) from \( \Delta I = \Delta n_{\text{photo}} \mu ES \), where \( E = 3.2 \times 10^6 \text{ V cm}^{-1} \) represents the electric field, \( S = 7.9 \times 10^{-8} \text{ cm}^2 \) is the cross-section area of MoS2, and \( \mu = 0.53 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1} \). The decrease of \( I_{\text{sd}} \) due to \( V_g \) erasing is indicated as \( \Delta I_g \), which gradually increases as \( V_g \) increases from 10 to 100 V and approaches \( \Delta I_g \) (Fig. 5B). Correspondingly, the removed electron \( \Delta n_{\text{gate}} \) in MoS2 increases from \( 0.6 \times 10^{24} \) to \( 2.2 \times 10^{24} \text{ cm}^{-3} \) and then saturates at ~\( 2.5 \times 10^{24} \text{ cm}^{-3} \) (Fig. 4C), which is close to photogate-induced \( \Delta n_{\text{photo}} \) (\( 2.4 \times 10^{24} \text{ cm}^{-3} \)) in MoS2. The above observation is consistent with our theoretical simulation that the transferred electrons from MoS2 to PbS increase with increasing \( V_g \) (Fig. 4B). Then, the localized holes gradually recombine with the electrons from MoS2 to PbS. Thus, we find that \( I_{\text{sd}} \) fully recovers its preillumination state (\( I_{\text{sd}}^0 \)) using a large \( V_g \) pulse.

The temperature \( (T) \)-dependent PPC (Fig. 5B) in device no. 4 becomes weaker as \( T \) increases from 100 to 180 K, and it disappears at 200 K. All other devices also present significant persistent photoconductances at low temperatures. However, no PPC is observed at room temperature. The localized holes can escape from the traps due to strong thermal fluctuations at high temperatures. This excludes the mechanism of random local potential fluctuations due to intrinsic defect and charged impurities states. The PPC of random local potential fluctuations \( (25) \) should be obvious at high temperatures because the localized trap centers release and play the role at high temperatures \( (26) \). The limitation of the operating temperature can be improved by interface engineering \( (27) \). For example, inserting a passivating buffer layer TiO2 at the interface of PbS and MoS2 \( (28) \) significantly increases the potential barrier height of trapped holes in PbS, which makes the localized holes robust against thermal fluctuations. However, the thickness of a buffer layer should be carefully chosen to ensure the tunneling of electrons from MoS2 to PbS for erasing process. We further discuss the roles of disorder states on the optical memory in note S3. We also exclude the photothermal effect or Schottky barrier effect from physical origins of optical memory (note S4).

**Nonvolatile operation of optical memory**

The charge storage stability is an important parameter to characterize the optical memory. Figure 6A presents the retention performance of laser pulse–intrigued persistent photocurrents with a measurement range of \( ~1.7 \times 10^4 \text{ s} \). The light power density is \( 27 \mu \text{W cm}^{-2} \) with a pulse width of \( 5 \text{ s} \). The readout current almost fully retrieves the original state even if the device is powered off for \( 10 \text{ min} \) and \( 1 \text{ and } 3 \text{ hours} \). The readout current hardly decays during the entire experimental range, indicating the potential of nonvolatile charge storage. The endurance of optical writing and electrical erasing is another critical factor for practical applications. As demonstrated in Fig. 6B, on and off states are hardly changed during the entire 2000 cycles of writing and erasing operations. We further demonstrate a multilevel memory in device no. 3, which can lead to an optoelectronic arithmetic function. Figure 6C shows four distinct resistance states, which are proprogrammed by three continuous laser pulses with \( 1 \text{-s duration} \). The readout current gradually increases with the application of three laser pulses. The readout charge is nearly linearly dependent on the number of optical states before saturation, in which each state captures ~\( 8.1 \text{nC} \) on average (Fig. 6D).

**DISCUSSION**

In our devices, the lifetime of localized holes is as large as \( 5125 \text{ s} \). However, the transit time of the photoexcited electrons in MoS2 is only \( 2.9 \text{ ns} \). As a result, the photoexcited electrons cycle multiple times in
respectively. Our device shows a longer lifetime of localized carriers that retains its original state even if the device is powered off for 10 min and 1 or 3 hours. The infrared pulse intrigues a persistent photocurrent state. The readout current fully retrieves memory states, even if the device is powered off. We then analyze the writing ($\tau_{\text{writing}}$) and erasing ($\tau_{\text{erasing}}$) time in five devices. The optimal $\tau_{\text{writing}}$ of 15.7 ms and $\tau_{\text{erasing}}$ of 0.17 s are observed in device no. 1 (inset of fig. S2F). The $\tau_{\text{writing}}$ describes the optical memory speed, which is affected by the light power density, carrier mobility in PbS and MoS$_2$, surface or interface disorders (26), thickness of PbS nanolayers, and channel length of MoS$_2$. $\tau_{\text{erasing}}$ relates to the recombination speed of electrons in MoS$_2$ with trapped holes in PbS. The $\tau_{\text{erasing}}$ can be improved by optimizing the interface potential width with the buffer layer. In addition, the surface or interface treatments (35), to vanish the influence from the surface or interface disorders states, are possible routes to improve the memory speed and increase the on/off ratio while decreasing the background noise.

We proposed a nonvolatile optical memory cell of MoS$_2$-PbS heterostructures that efficiently works in the optical communication wavebands. The devices operate via the photogate effect, which leads to the persistent retention of charges without any external voltage bias. The readout current fully retrieves memory states, even if the device is powered off for 3 hours, and hardly decays within our measurement range (more than $10^5$ s), suggesting a promising nonvolatile charge storage device. The buffer layer can further improve the charge storage stability by increasing the width of charge-free region. Our devices are robust to uncontrolled environmental factors such as surface and interface impurities or defects. However, the devices have the temperature limitation of memory effect disappearing above 200 K, which can be improved by inserting the buffer layer. Nevertheless, the demonstrated devices show a long-term stability (2000 cycles), signifying their promise in the infrared memory, optoelectronic arithmetic, and logic circuit.

MATERIALS AND METHODS

Synthesis and characterization

Few-layer MoS$_2$ flakes were mechanically exfoliated from MoS$_2$ bulk crystals and were transferred to SiO$_2$ (300 nm)/n$^{++}$-Si substrates. The substrates with few-layer MoS$_2$ flakes were cleaned by hot acetone (100°C) for removing surface residues. Then, the samples were placed in the downstream of quartz tube of a high-temperature furnace. The quartz tube was pumped to 20 Pa, and the exfoliated few-layer MoS$_2$ was annealed in a vacuum for half an hour at 650°C. During the annealing, the tube was fed by hydrogen gas with a flow rate of 20 standard cubic centimeters per minute. Subsequently, PbS nanolayers were grown on the few-layer MoS$_2$ via thermal evaporation of PbS powder (99.99%; Alfa Aesar). The source and substrate temperatures were set to 750°C and 550°C for 2 min, respectively. The furnace was then naturally cooled down after the growth. The materials were characterized by HRTEM in FEI Tecnai F20 with SAED and XPS (ESCALAB 250 Xi).

Device fabrication

The electrodes were fabricated by standard electron beam lithography (Nova 200 NanoLab). The defined pattern was successively coated by 10-nm Ti and 40-nm Au thin films via a magnetron sputtering system.
Then, the pattern was lifted off using acetone. The device morphology and dimensions were characterized by scanning electron microscopy (Zeiss) and atomic force microscopy (Dimension 3100, Veeco).

Optoelectronic characterization
All optoelectronic transport was performed on a manual probe station (TTP4, Lakeshore) equipped with a vacuum chamber and temperature control system. Keithley 4200 semiconductor parameter analyzer was used to collect the data. The focused infrared lasers with wavelengths of 808, 1340, and 1550 nm were applied to illuminate the samples. The laser pulses were produced by a chopper. The back gate voltage pulses were generated by a wave generator. The spot size was obtained by shining the infrared laser on the detector cards (THORLABS VRC4 and VRC6S). The VRC4 converted 808-, 1340-, and 1550-nm lasers to visible light. VRC6S changed color when it was excited by a 1940-nm laser. Taking a 1550-nm laser as an example, we used the camera to record the image of laser spot on a detector card. The vernier caliper was placed nearby the laser spot to identify the diameter of laser spot.

Numerical simulation
The physical model of light illumination- and gate voltage-modulated current density and \( V_g \) pulse-induced erasing in MoS\(_2\) was derived from the theory of thermionic emission, quantum tunneling, and diffusion transport (see notes S1 and S2). Simulations for the change of carrier density induced by photo injection and \( V_g \) injection were based on the capacitance effect of back gate voltages.

SUPPLEMENTARY MATERIALS
Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/4/eaap7916/DC1
fig. S1. Chemical and structural characterization.
fig. S2. Device morphology and optoelectronic transport.
fig. S3. Control experiments on few-layer MoS\(_2\).
fig. S4. Photoresponse in PbS nanoplate with an 808-nm laser illumination.
fig. S5. The optoelectronic transport and optical memory.
fig. S6. Photoresponse performance.
fig. S7. \( V_g \) pulse–dependent erasing current.
fig. S8. Optoelectronic transport and on/off ratio.
fig. S9. Persistent photocurrent as a function of time after the laser pulse switches off.
fig. S10. Optoelectronic transport and optical memory.
fig. S11. Number of transferred electrons as a function of the Fermi level shift.
table S1. Memory performance of five devices.
note S1. Theoretical simulation of carrier injection to MoS\(_2\).
note S2. Dynamics analysis of \( V_g \) pulse erasing.
note S3. Roles of disorder states on the optical memory.
note S4. Photothermal effect or Schottky barrier effect.
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Acknowledgments
Funding: This work was partially supported by the Ministry of Science and Technology of China (no. 2016YFA0200700), National Natural Science Foundation of China (nos. 61625401, 61474033, and 61574050). Strategic Priority Research Program of the Chinese Academy of Sciences (CAS) (grant no. XDA09040201), and CAS Key Laboratory of Nanosystem and Hierarchical Fabrication. We also acknowledge the support of CAS Youth Innovation Promotion Association. H.Y. thanks the support from the A*STAR’s Pharos Programme on Topological Insulators, Ministry of Education–Singapore Academic Research Fund Tier 1 (R-263-000-847-112) and Tier 2 (R-263-000-B10-112). C.J. acknowledges the support from the National Natural Science Foundation of China (nos. 11374070 and 21432005). Author contributions: Q.W., Y.W., and J.H. conceived and designed the projects. Y.W. carried out the synthesis and characterization. Q.W. and Y.W. performed the optoelectronic measurements. K.C. performed the theoretical simulation. R.C. and L.Y. assisted the experiments. Q.W. and H.Y. wrote the manuscript with the input from all other authors. J.H., C.J., and H.Y. supervised the projects. Competing interests: The authors declare that they have no competing interests. Date and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 4 September 2017
Accepted 1 March 2018
Published 20 April 2018

Citation: Q. Wang, Y. Wen, K. Cai, R. Cheng, L. Yin, Y. Zhang, J. Li, Z. Wang, F. Wang, F. Wang, T. A. Shifa, C. Jiang, H. Yang, J. He, Nonvolatile infrared memory in MoS₂/PbS van der Waals heterostructures. Sci. Adv. 4, eaap7916 (2018).