Supporting Information

Infrared Detectable MoS_2 Phototransistor and Its Application to Artificial Multi-Level Optic-Neural Synapse

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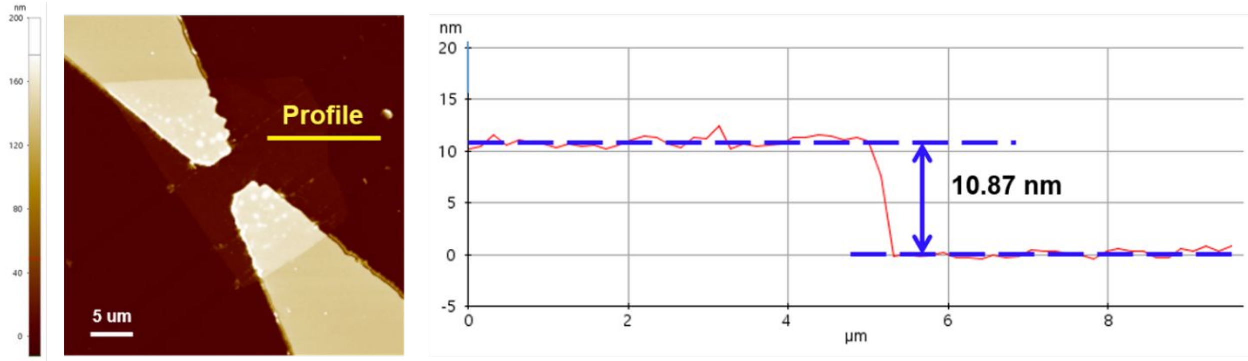

Figure S1. AFM image and height profile of the MoS_2 flake. Figure S1 shows AFM image and height profile of the MoS_2 flake used in this work. The thickness of the MoS_2 flake was measured as approximately 10.87 nm, which corresponds to approximately 15 layers of MoS_2, because the thickness of one layer was 0.6–0.7 nm.

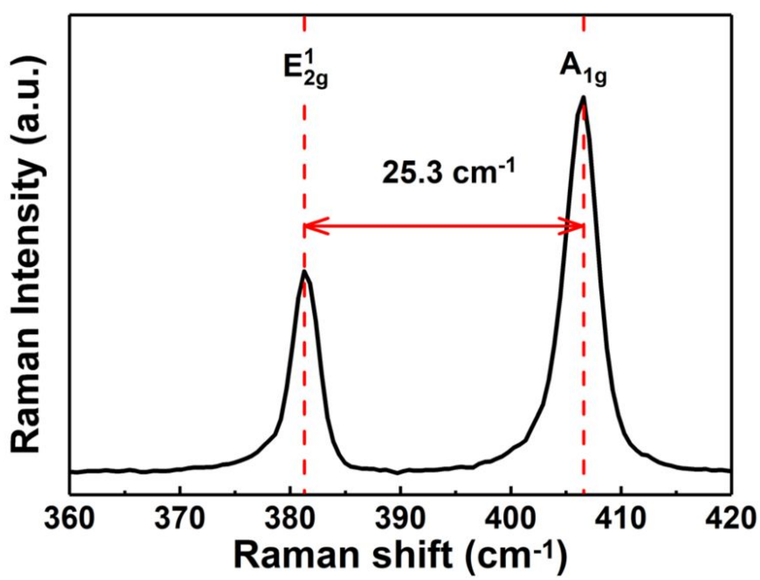

Figure S2. Raman spectra of the exfoliated MoS_2 flake. Two different Raman peaks were observed near 381.3 and 406.6 cm^{-1} under excitation by a 532 nm line, as shown in Figure S2. For comparison with a previous report, the MoS_2 flake used in this work had >5 layers.

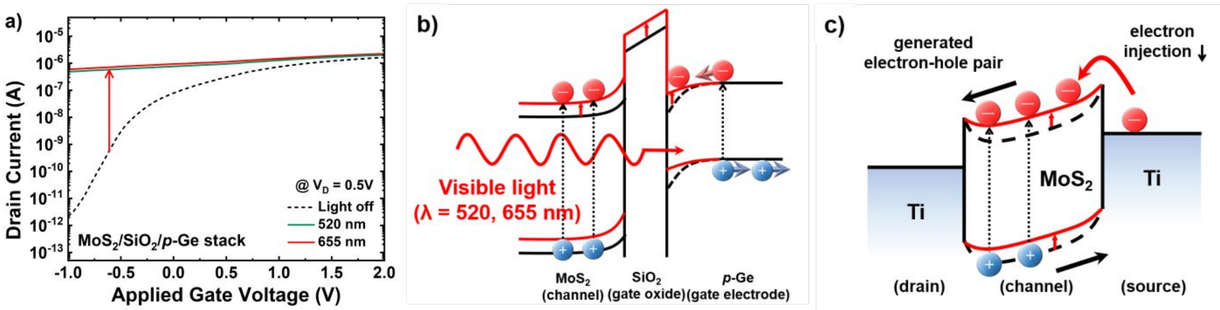

Figure S3. a) Optical characterization of the Ge-gated MoS_2 phototransistor under visible light (λ = 520 and 655 nm) and the energy band diagrams for b) the vertical direction and c) the horizontal direction. In contrast to the optical characteristics under infrared light, the I_D increased by a factor of >1000 at V_G = -0.5 V and V_D = -0.5 V under visible light, as shown in Figure S3a. This is explained by the band diagrams. When the visible light was incident onto the device, electron–hole pairs were generated in both the Ge gate and the MoS_2 channel, as shown in Figure S3b. The electron–hole pairs generated in the Ge gate obstructed the current conduction through the MoS_2 channel by modulating the electrostatic potential of the channel at the same gate bias. However, the electron–hole pairs generated in the MoS_2 channel induced a large photocurrent, increasing the drain current. Although the two mechanisms yielded opposite results in the current-conduction characteristics of the phototransistor, a large increase in I_D was observed, because the induced photocurrent at the MoS_2 channel was the dominant factor, as shown in Figure S3c.

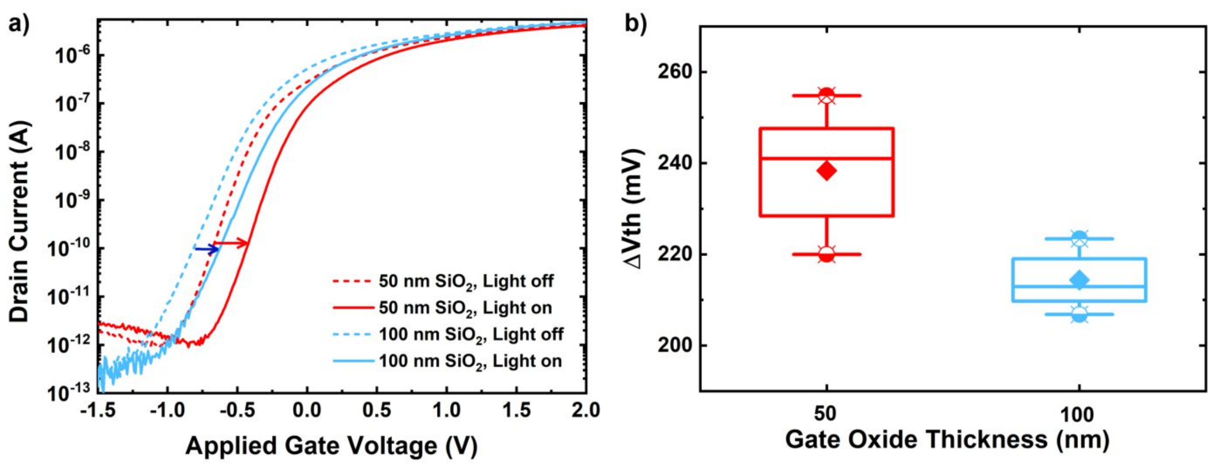

Figure S4. a) Electrical transfer curves of the Ge-gated MoS_2 phototransistor with 50 and 100 nm-thick SiO_2. b) An amount of threshold voltage shifting versus gate oxide thickness. An average amount of threshold voltage shifting by irradiated infrared light decreases from 238 mV to 214 mV as the thickness of SiO_2 increases inducting the capacitance reduction.

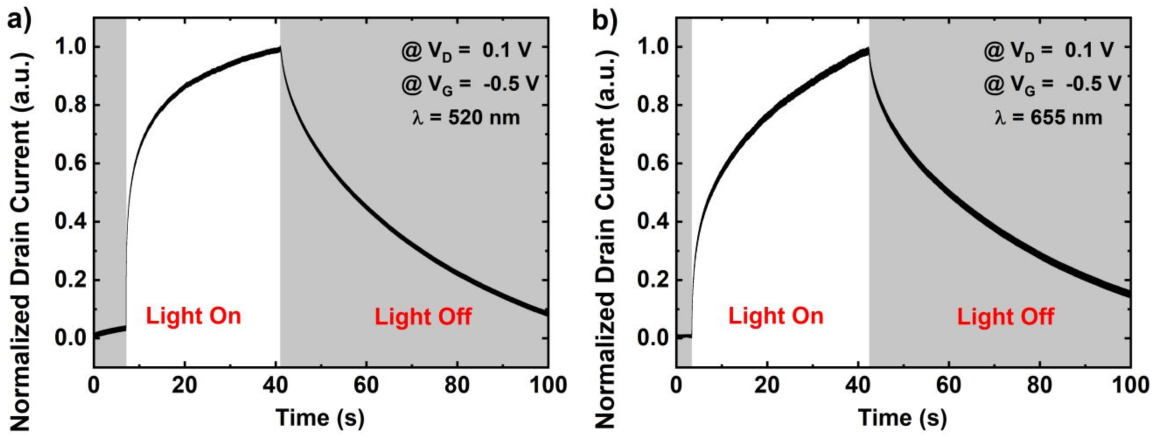

Figure S5. Temporal responses of the device a) under 520 nm light and b) 655 nm light at a V_D of 0.1 V and a V_G of -0.5 V. The normalized drain current is plotted as a function of measurement time durations and the rising and decaying time values can be extracted between 10% and 90% of the increasing and decreasing drain current, respectively. The responses to the visible light are similar to the results of previous studies: the rising time is 15.67 s for λ = 520 nm and 28.67 s for λ = 655 nm, and the decay time is 52.91 s for λ = 520 nm and 61.33 s for λ = 655 nm.

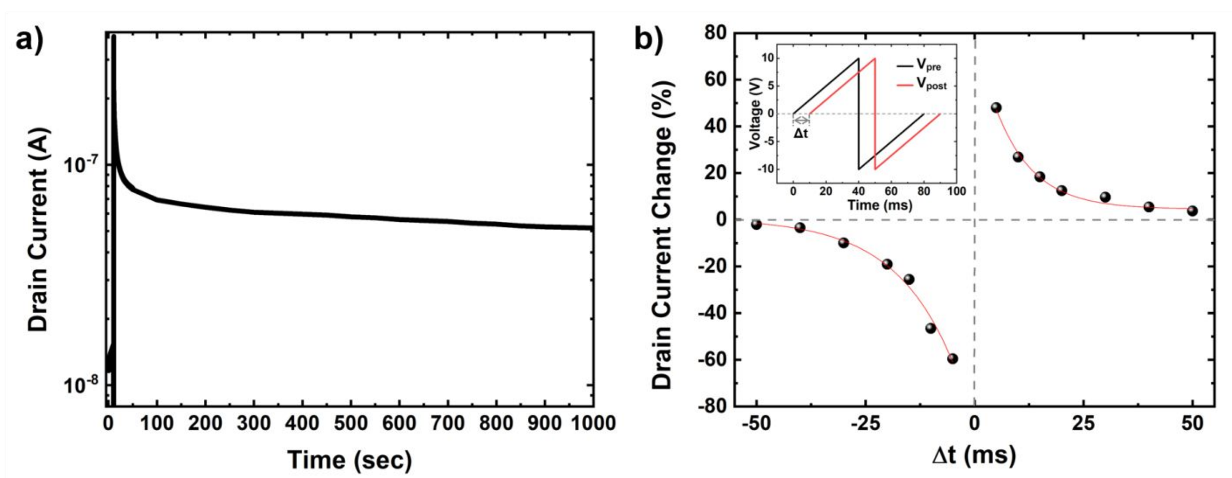

Figure S6. B**asic synaptic behaviors of Ge-gated MoS_2 phototransistor. a) Synaptic currents triggered by a single gate pulse. b) Spike-timing-dependent plasticity (STDP) behavior.** Figure S6a shows the decay of synaptic currents triggered by a single gate pulse of -30 V in amplitude and 50 ms in duration. Figure S6b shows the STDP behavior of the device. The drain current change ($\Delta I/I_0$) measured at V_D = 0.5 V after presynaptic and postsynaptic spikes are applied with a time difference, $\Delta t = t_{post} - t_{pre}$, where t_{post} and t_{pre} are the time when the presynaptic and postsynaptic pulses spike, respectively. If the presynaptic spike occurs before the postsgynaptic spike ($\Delta t > 0$), the device undergoes a potentiation. And, if the postsynaptic spike occurs before the presynaptic spike ($\Delta t < 0$), the device undergoes a depression.

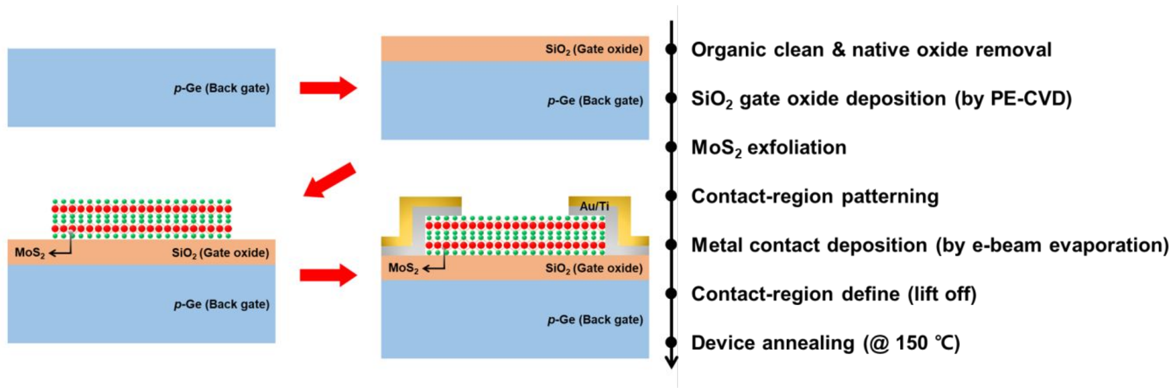

Figure S7. Schematics showing the fabrication process for the $MoS_2/SiO_2/Ge$ phototransistor. To use p-Ge for the back-gate electrode, the conventional gate oxide, SiO_2, was deposited on the Ge substrate *via* PE-CVD. The few-layer MoS_2 was exfoliated using PDMS tape *via* the micromechanical exfoliation method, because PDMS tape is effective for obtaining large and uniform flakes.

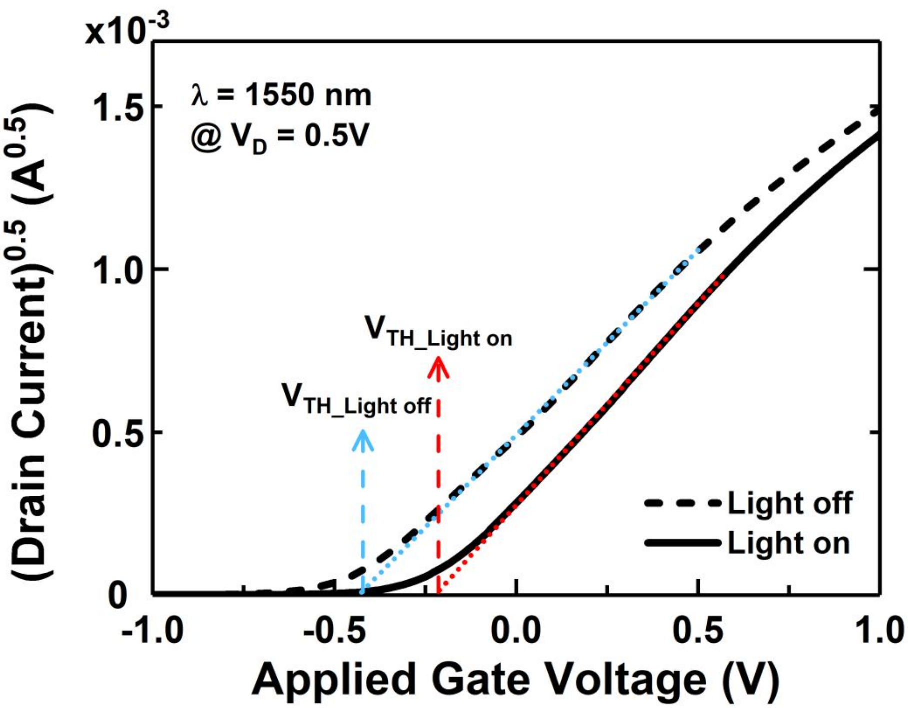

Figure S8. $I_D^{0.5}$–V_G characteristics of the device for extracting the threshold voltage. The threshold voltage was calculated using the equation $I_D = K(V_G - V_{TH})^2$, where I_D is the drain current, K is a constant, V_G is the applied gate voltage, and V_{TH} is the threshold voltage. Thus, in the square root of the drain-current curve as a function of applied gate voltage, the V_{TH} is derived by the x-intercept points of the tangential lines in the linear region of the curves.