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Supplementary Information for

2D Electric-Double-Layer Phototransistor for Photo-Electronic and Spatio-Temporal Hybrid Neuromorphic Integration

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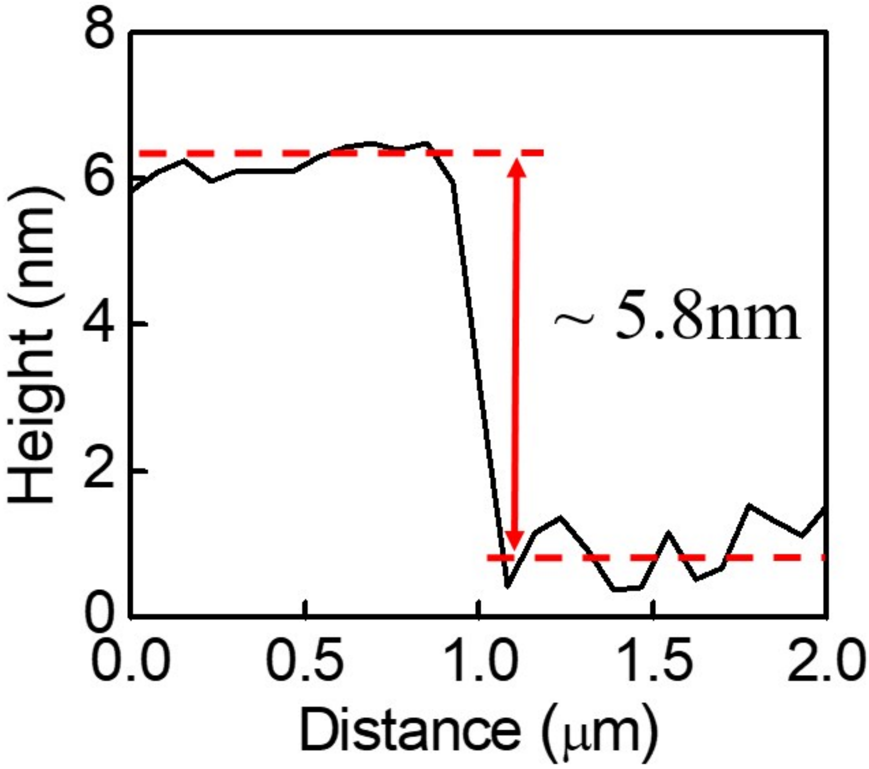


Fig. S1 The thickness of the MoS_2 flake measured by AFM.

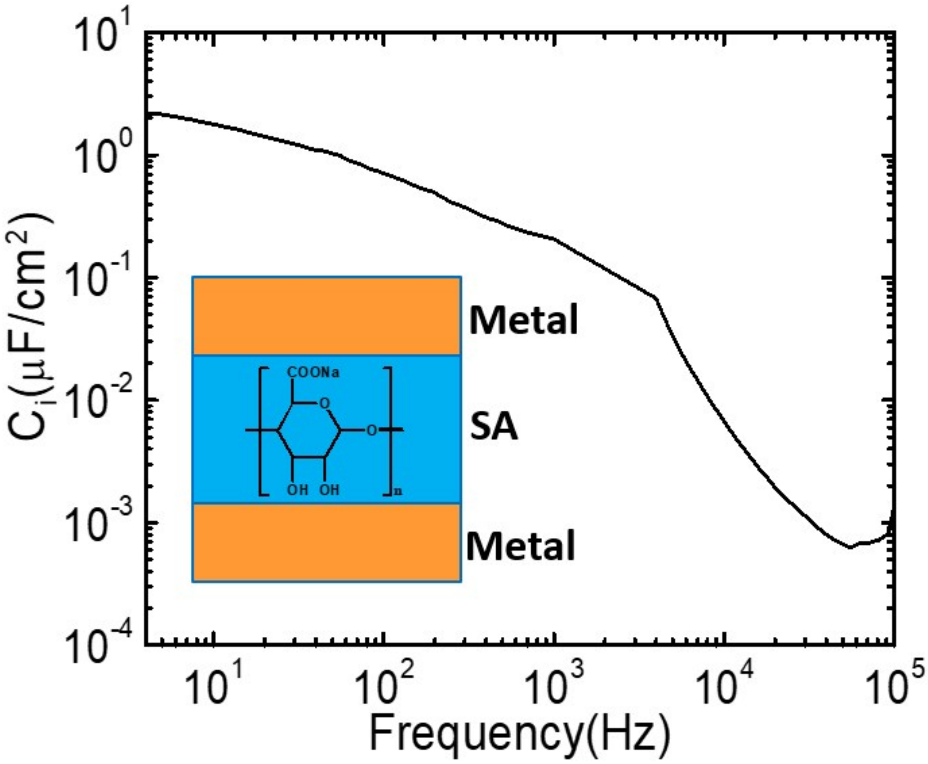


Fig. S2 Frequency-dependent capacitance characteristic of the sodium alginate electrolyte. Inset: a vertical metal/ sodium alginate /metal sandwich structure.

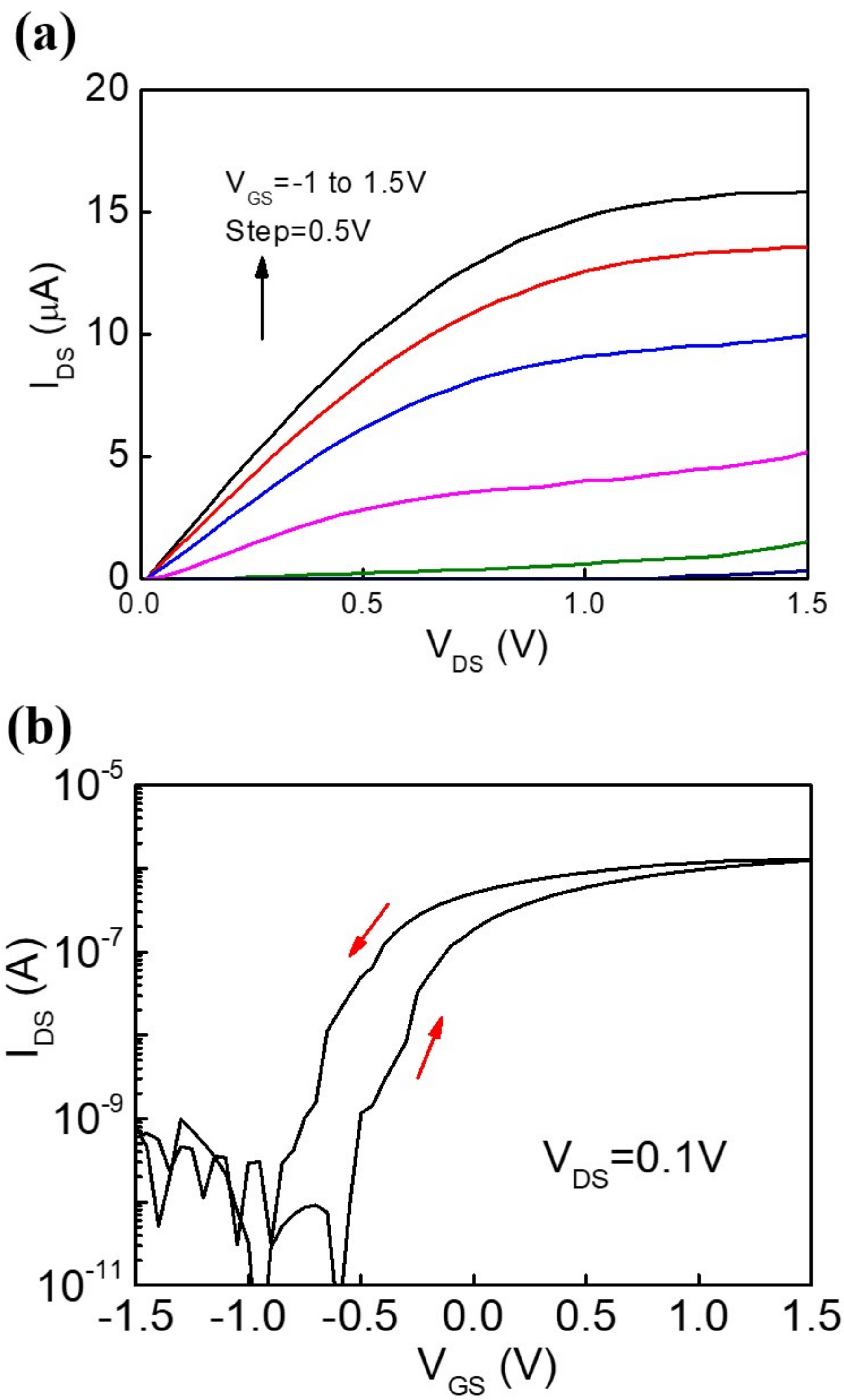


Fig. S3 (a) The output characteristics of the MoS_2 transistor. (b) The transfer curves of the MoS_2 transistor.

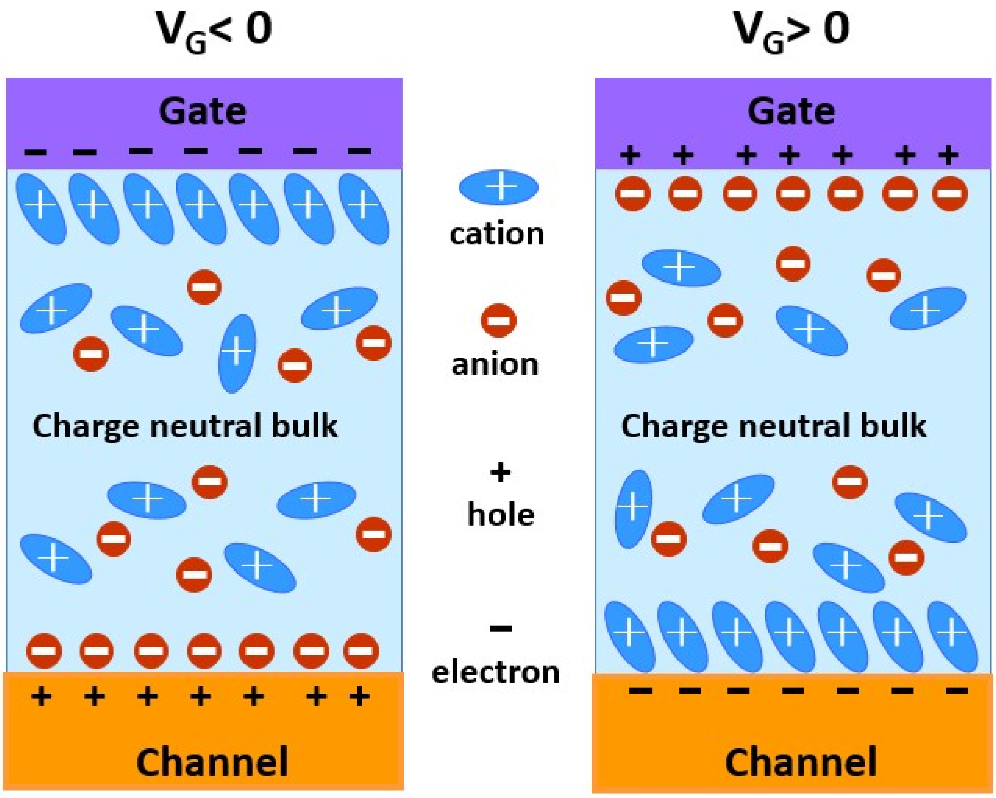


Fig. S4 Schematic diagram illustrating the dynamic processes of electric-double-layer (EDL) formation under negative ($V_G < 0$) and positive ($V_G > 0$) gate bias.

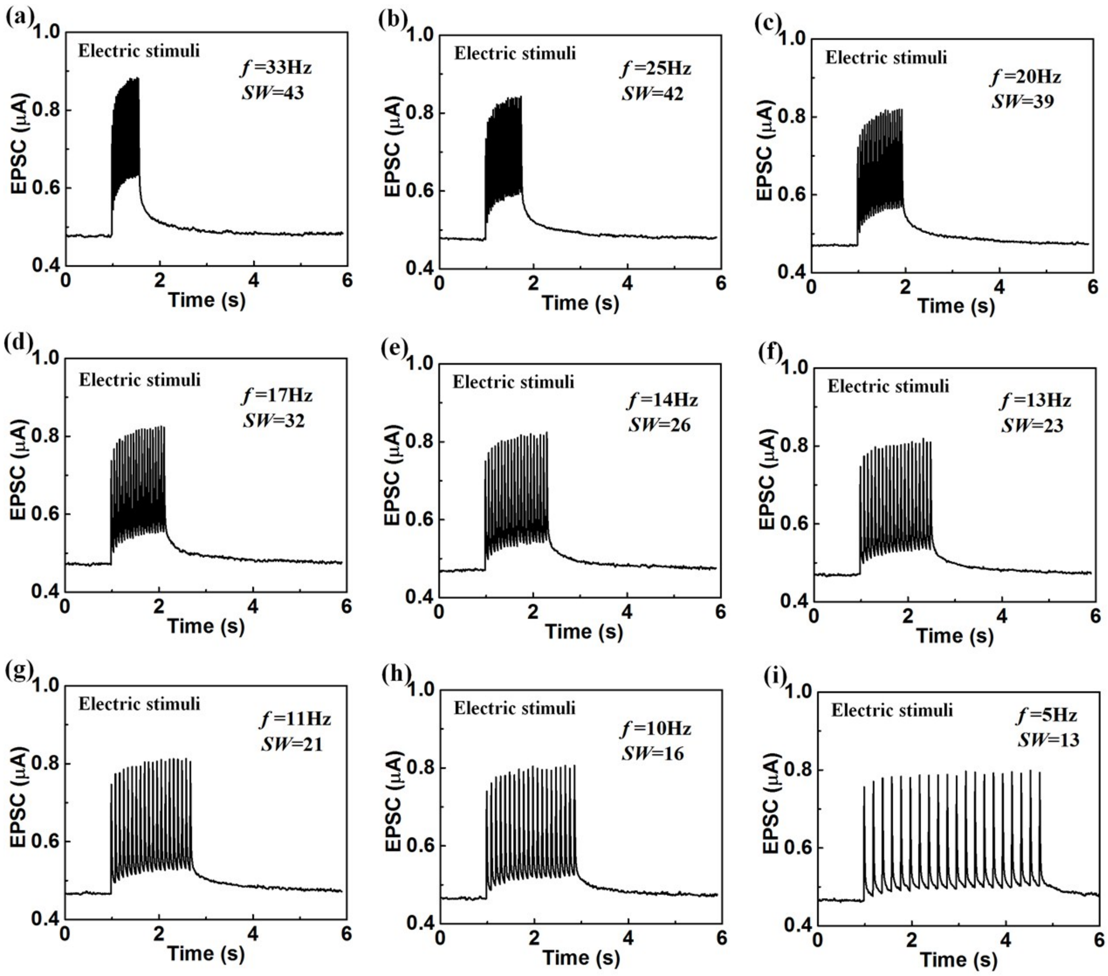
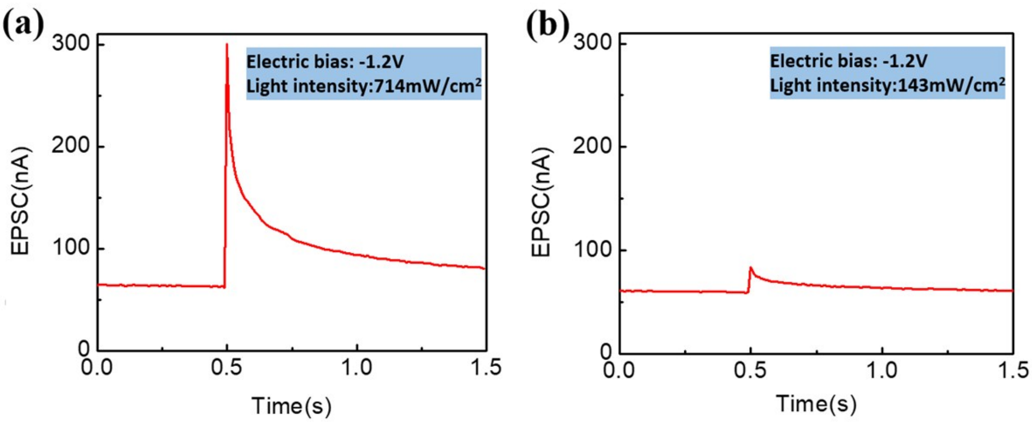


Fig. S5 EPSC responses recorded in response to the electric stimulus train with different frequencies (a) f = 33Hz; (b) f = 25Hz; (c) f = 20Hz; (d) f = 17Hz; (e) f = 14Hz; (f) f = 13Hz; (g) f = 11Hz; (h) f = 10Hz; (i) f = 5Hz.



(c)

Light intensity (mW/cm²) / ΔEPSC (nA) / Electric bias (V)	143	428	714
-0.7	6	112	182
-0.8	11	124	210
-0.9	16	143	221
-1.2	24	167	238

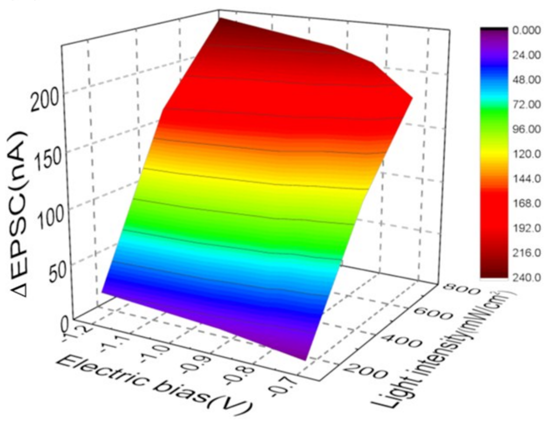


Fig. S6 EPSC responses triggered by a light spike (405nm, 10ms) at V_{GS}=-1.2V with light intensities of (a)714 mW/cm^{-2} and (b)143 mW/cm^{-2}. (c) Table: the experimental results of ΔEPSC under different conditions. (d) a 2D EPSC surface.

We made a new MoS_2 transistor to investigate the modulation of currents with simultaneous operation of photo-electric modes. The typical I-t characteristics of the device under different intensities of light illumination (405nm, 10ms) are respectively shown in Figures S6a and S6b above with a fixed electric bias of -1.2V. Obviously, a larger light intensity corresponds to a larger EPSC response. Furthermore, we execute a series of I-t tests by combination of several light intensities (143, 428 and 714 mW/cm^{-2}) and several gate voltages (-0.7, -0.8, -0.9 and -1.2 V). The detailed experimental results are systematically summarized in the table in Figure S6c above, where ΔEPSC refers to the difference value between the EPSC peak and baseline current. To more clearly analyze the modulation of currents, a 2D EPSC surface can be plotted as a function of the electric bias and light intensities, as shown in Figure S6d above. From this figure, it is clearly observed that the amplitude of EPSC can be continuously tuned accordingly and a larger light intensity and a more negative electric bias would result in a larger EPSC response.

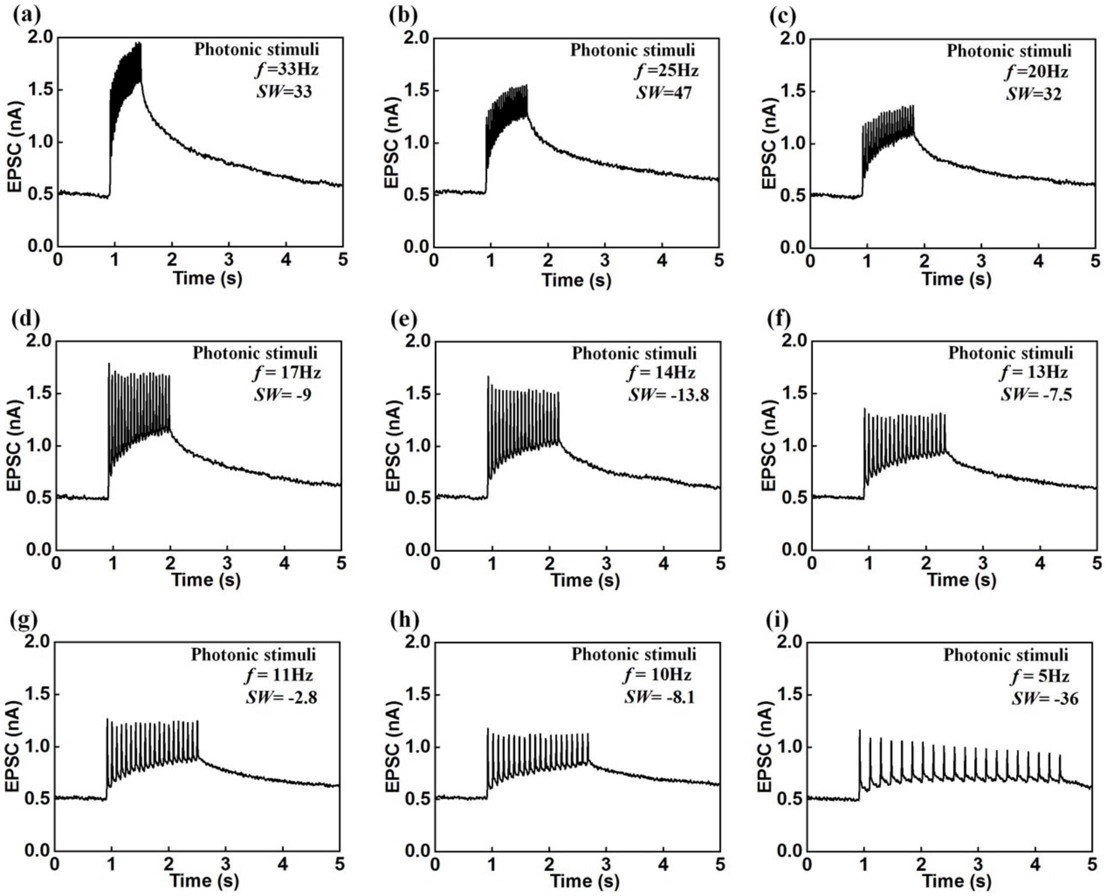


Fig. S7 EPSC responses recorded in response to the photonic stimulus train with different frequencies (a) f = 33Hz; (b) f = 25Hz; (c) f = 20Hz; (d) f = 17Hz; (e) f = 14Hz; (f) f = 13Hz; (g) f = 11Hz; (h) f = 10Hz; (i) f = 5Hz.

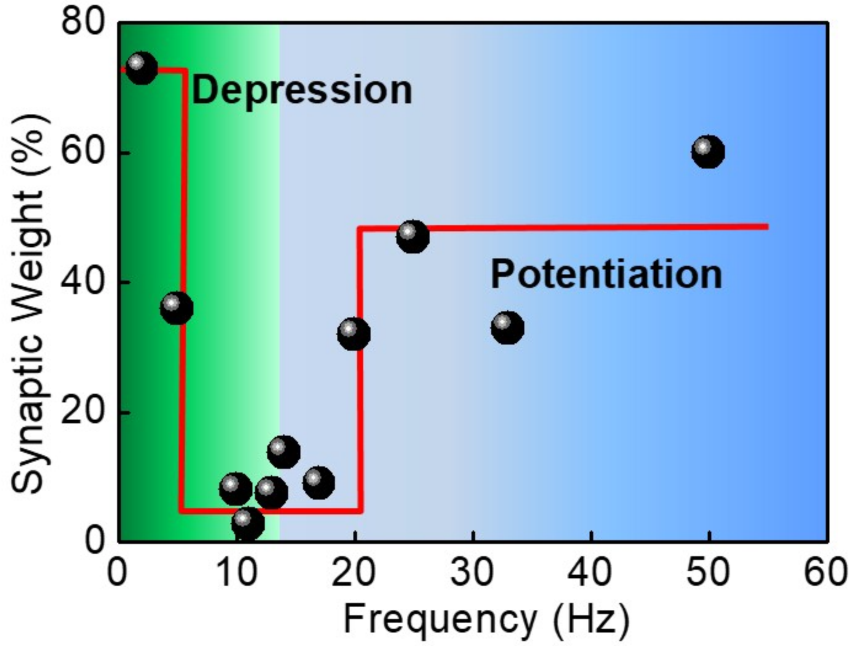


Fig. S8 Synaptic weight (*SW*) plotted as a function of presynaptic spike frequencies. The red solid line: the fitting model.

We try to extend the filtering characteristics. If the change of synaptic weight is defined as $SW = |(A_{20}\text{-}A_1)/A_{1*}100\%|$, the relationship between frequency and synaptic weight will change for the photonic operation mode, as shown in Fig. S8 above. In this case, the experimental data can be qualitatively explained by the fitting model (red solid line). As we clearly see, the synaptic weight becomes weak within a specific frequency range (6~20 Hz). In biological nervous system, such synaptic function is a band-stop filtering that passes most frequencies unaltered for the signal transmission from pre- to post-synaptic cell, but attenuates those in a specific range to very low levels [*Journal of Neuroscience*, 2011, **31**, 14721]. Therefore, we conclude that this important biological band-stop filtering function can also be realized via our photonic MoS_2 synaptic transistor.

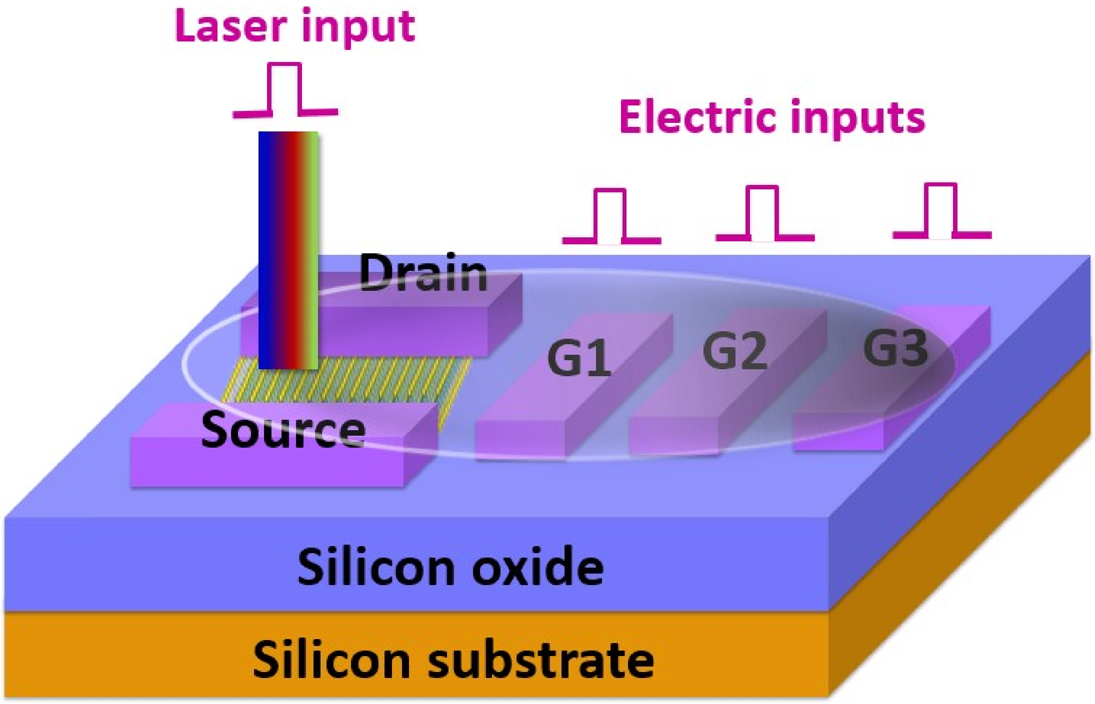


Fig. S9 Schematic of photonic-electronic hybrid MoS_2 transistor with multiple in-plane gates.

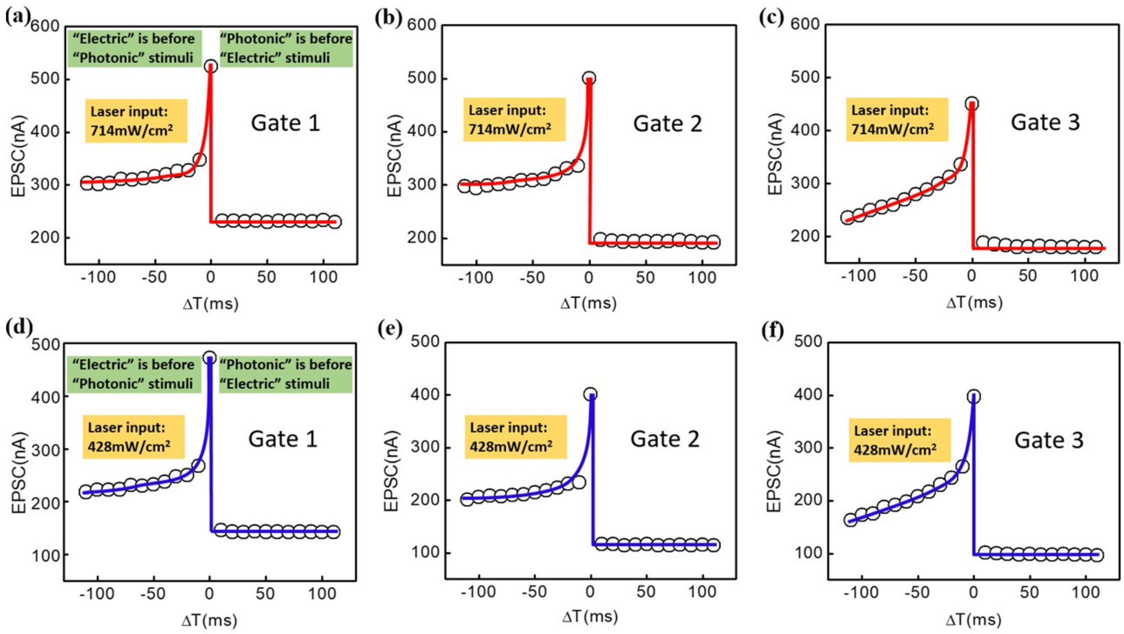


Fig. S10 The spatio-temporal correlation effects with different laser inputs and gate electrodes.

We made a new device with multiple in-plane gates to further demonstrate the spatial dependence of the two stimuli. as shown in Figures S9 and S10 above. Here, the amplitude of all the electric pulses stimuli we set are the same as 0.6V. From this figure, it is clearly seen that, under the identical laser light exposure, the EPSC amplitude decreases with the gate-to-channel distance increasing from 50μm to 150μm to 250μm (Gate1→Gate2→Gate3), indicating that the coupling effect of the two stimuli modes become weak accordingly. Moreover, we also find that the larger light intensity corresponds to the greater EPSC response for the same gate electrode (i.e. the same gate-to-channel distance), which is due to more photo-generated electron-hole pairs are generated in this case.

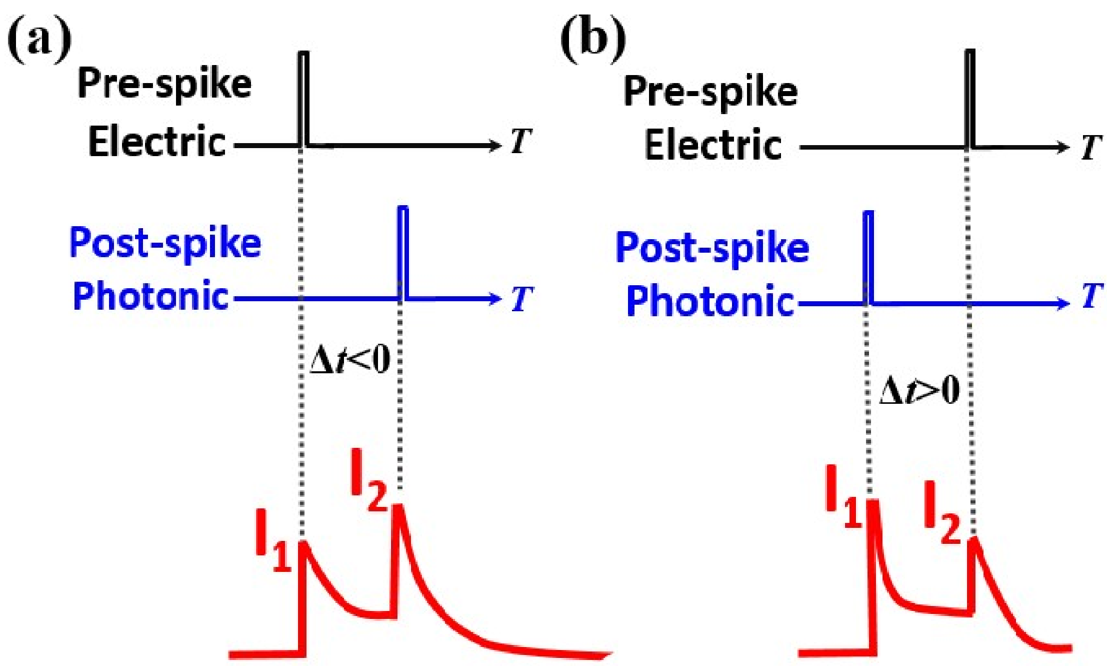


Fig. S11 Schematic diagram of STDP measurements under different conditions: (a) $\Delta t<0$. (b) $\Delta t>0$.

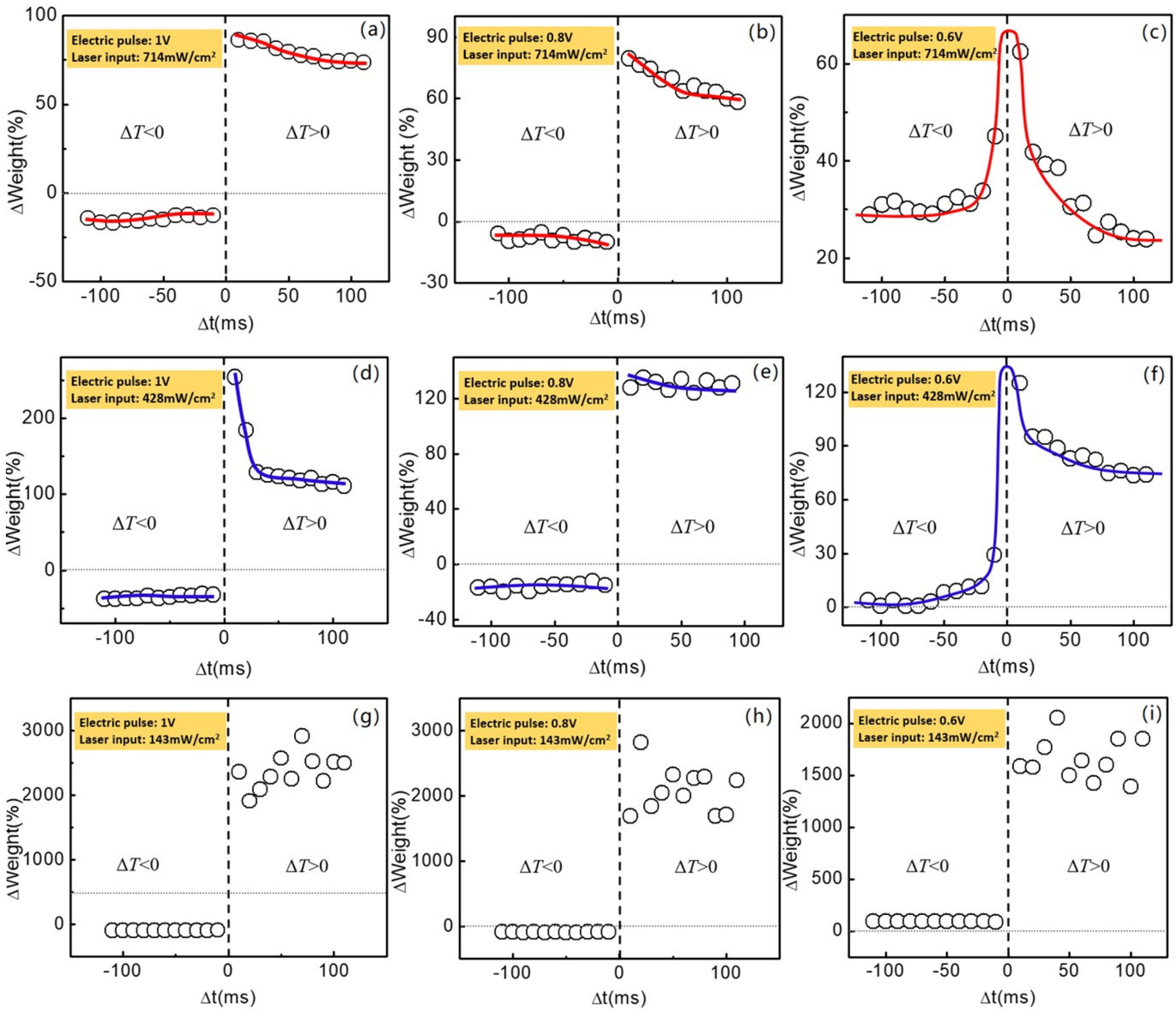


Fig. S12 Synaptic weight (ΔW) plotted as function of $\Delta t_{\text{pre-post}}$ ranging from -110 to 110 ms under the conditions of different laser inputs and electric pulses.

We made a new MoS_2 transistor to perform more comprehensive experiments on the photonic-electronic hybrid STDP behaviors, as shown in Fig. S12 above. The different amplitudes of the electric pulses (1, 0.8 and 0.6 V) and different light intensities (714, 428 and 143 mV/cm^2) are applied respectively. Obviously, when the laser light input is relatively larger, typical STDP characteristics can be observed. However, such characteristics disappear when the light intensity is reduced to 143 mV/cm^2, probably because such a weak the light illumination is unable to produce current responses matching that generated by the electric pulses. More interestingly, we can also find that, under the identical conditions of laser input, both asymmetric (electric pulse: 1V and 0.8V) and symmetric (electric pulse: 0.6V) STDP characteristics can be emulated by our MoS_2 synaptic transistors. In other words, STDP characteristics could be variable by adjusting the amplitudes of the electrical pulses and photonic pulses.