Supplementary Information

An All-in-One Biomimetic 2D Spiking Neural Network

Shiva Subbulakshmi Radhakrishnan[1], Akhil Dodda[1], and Saptarshi Das[1,2,3,]*

[1]*Department of Engineering Science and Mechanics, Pennsylvania State University, University Park, PA 16802, USA*

[2]*Department of Materials Science and Engineering, Pennsylvania State University, University Park, PA 16802, USA*

[3]*Materials Research Institute, Pennsylvania State University, University Park, PA 16802, USA*

Supplementary Information 1

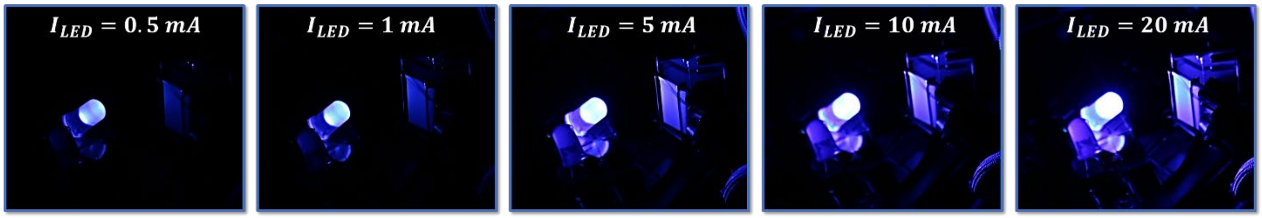

Figure S1: *Optical images showing different LED brightness levels for various* I_{LED}.

Supplementary Information 2

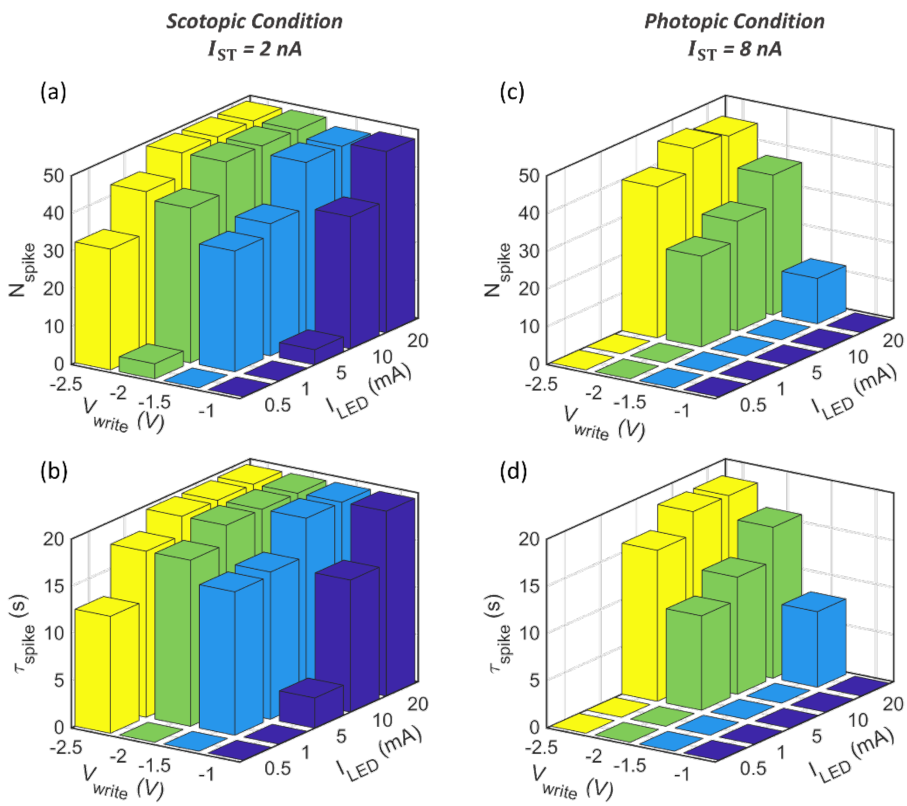

Figure S2: *a) Number of spikes (*N_{spike}*) and b) total spiking duration (*τ_{spike}*) as a function of* I_{LED} *and* V_{write}*, with* I_{ST} *= 2 nA. Decreasing the spiking threshold and illuminating the LED at* V_{write} *= -2.5 V allow encoding under scotopic (low-light) conditions. c) Number of spikes (*N_{spike}*) and d) total spiking duration (*τ_{spike}*) as a function of* I_{LED} *and* V_{write}*, with* I_{ST} *= 8 nA. Increasing the spiking threshold and illuminating the LED at* V_{write} *= -2 V allow encoding under photopic (bright-light) conditions.*

Supplementary Information 3

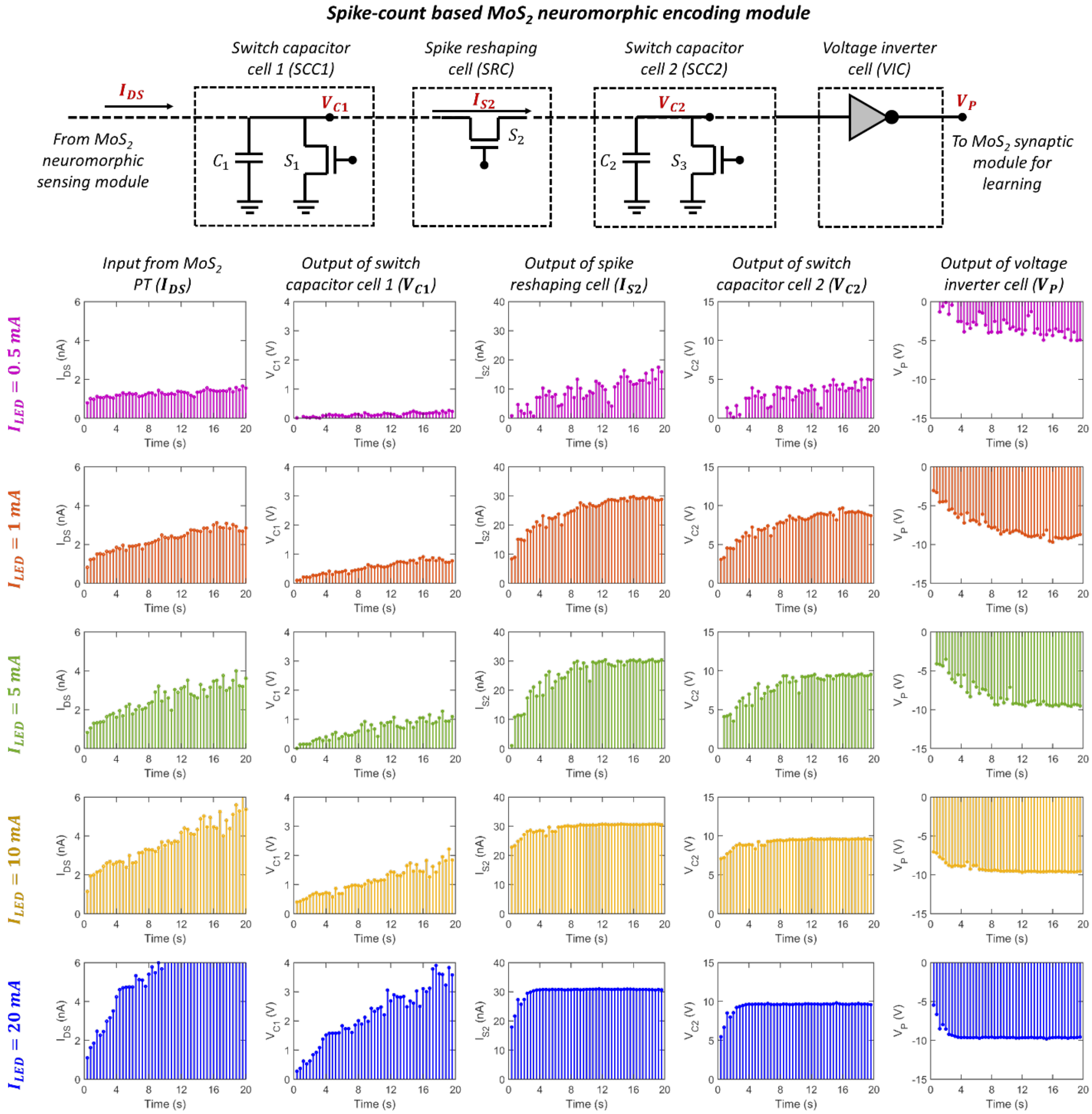

Figure S3: *I_{DS} spikes obtained from the MoS_2 PT biased at V_{write} = -1.5 V for different I_{LED}, and corresponding output of SCC1 (V_{C1}), SRC (I_{S2}), SCC2 (V_{C2}), and VIC (V_P).*

Supplementary Information 4

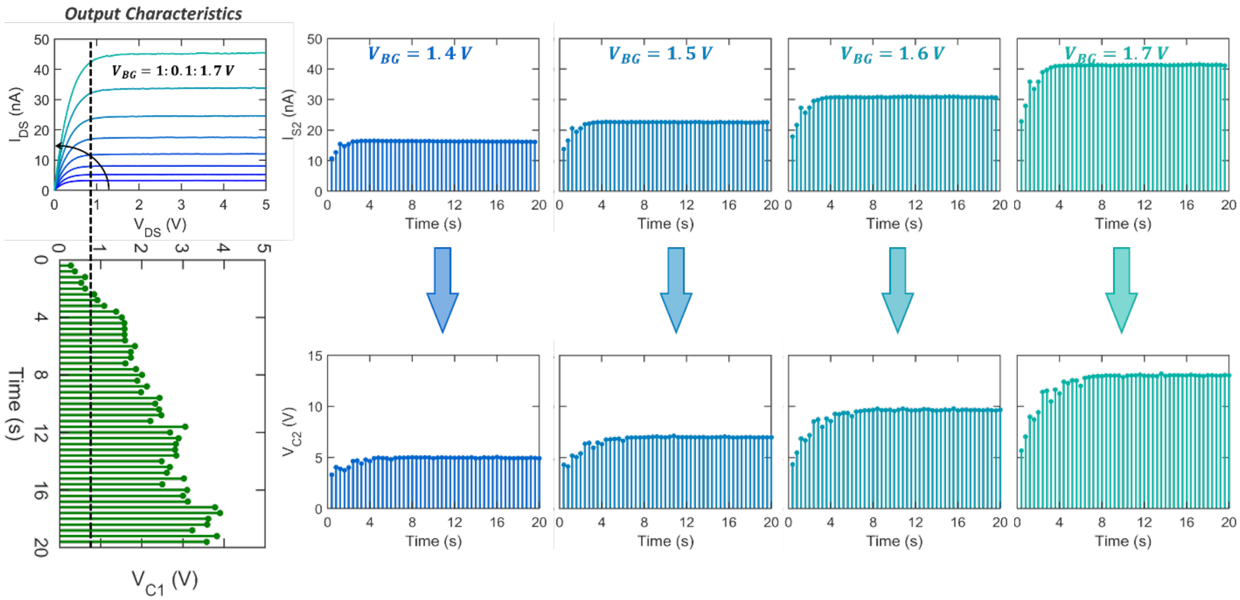

Figure S4: *Output characteristics of MoS_2 FET (S_2) illustrating current saturation for V_{C1} > 0.8 V, which corresponds to I_{DS} = I_{ST} = 3 nA. Depending upon the gate-bias of S_2, different magnitudes of I_{S2} spikes and subsequently, V_{C2} spikes can be obtained for the same set of V_{C1} spikes.*

Supplementary Information 5

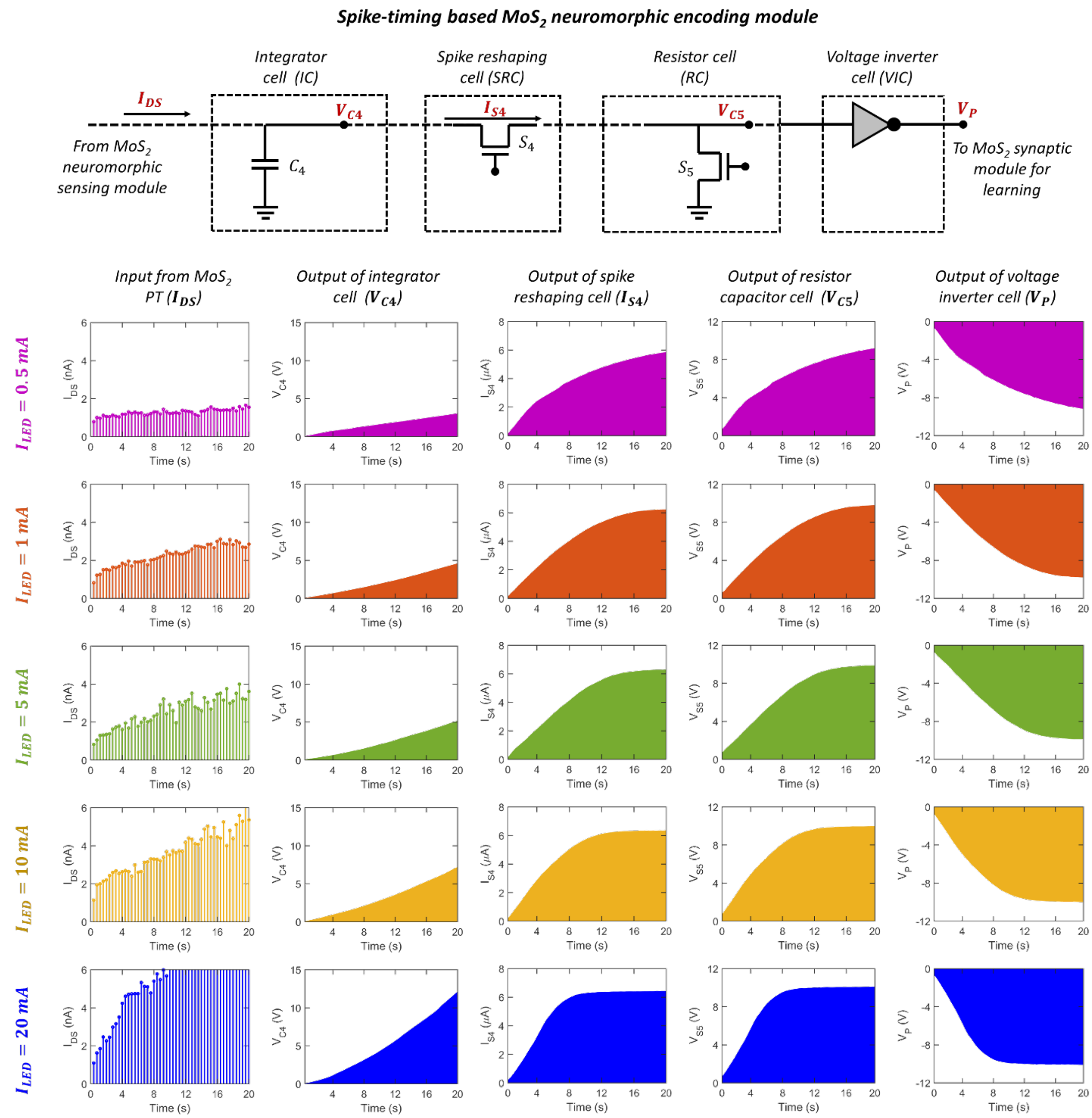

Figure S5: *I_{DS} spikes obtained from the MoS_2 PT biased at V_{write} = -1.5 V for different I_{LED}, and corresponding output of V_{C4}, I_{S4}, V_{S5}, and V_P.*

Supplementary Information 6

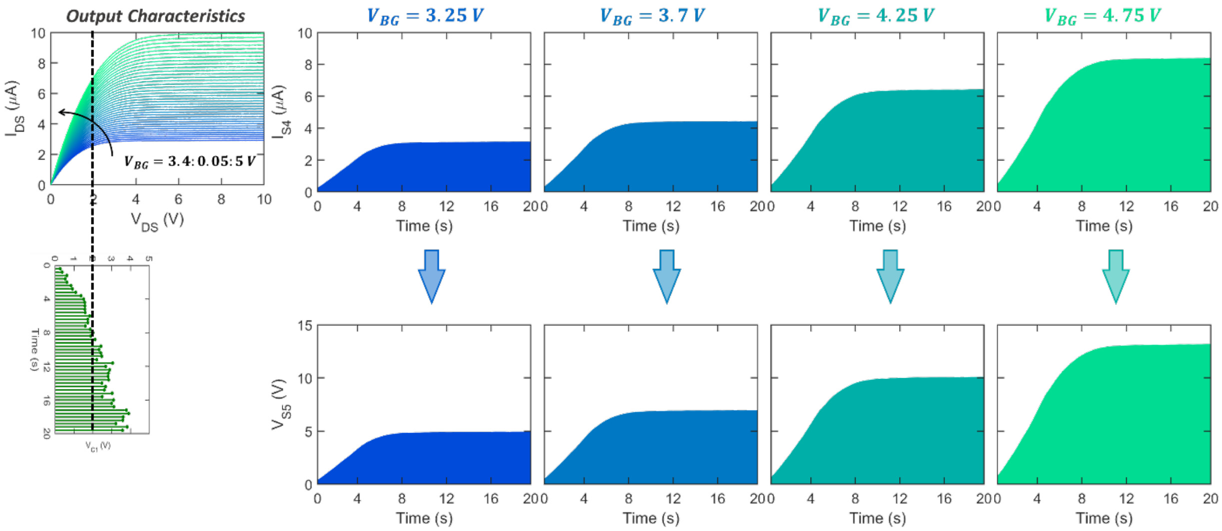

Figure S6: *Output characteristics of S_4 illustrating current saturation for $V_{C4} > 1.5$ V, which corresponds to $I_{DS} = I_{ST} = 3$ nA. Depending upon the biasing conditions of the S_4, different magnitudes of I_{S4} spikes and subsequently, V_{S5} spikes can be obtained for the same set of V_{C1} spikes.*

Supplementary Information 7

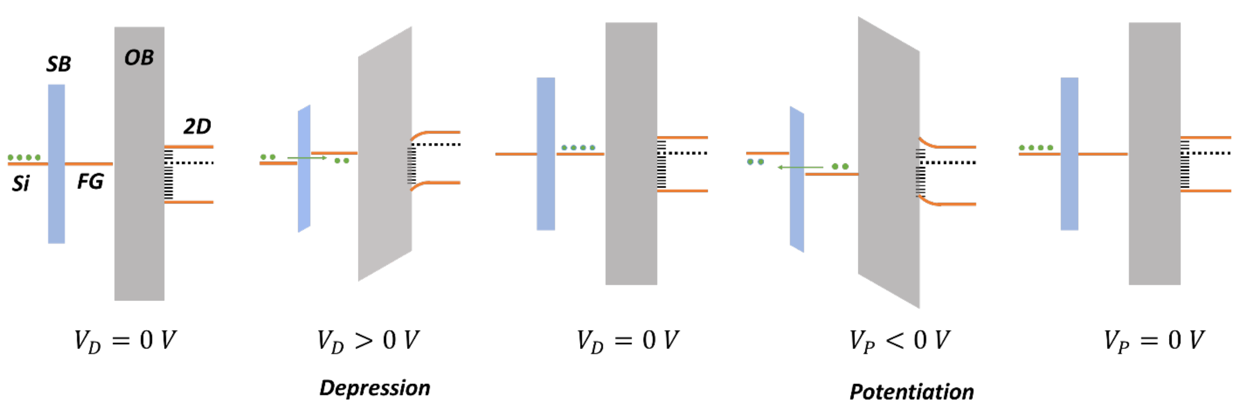

Figure S7: *Energy band diagrams showing the potentiation and depression operations. The p++-Si/TiN/Pt interface in the stack is characterized by a Schottky barrier (SB), whereas, the gate dielectric, i.e. 50 nm Al_2O_3, acts as an oxide barrier (OB). The OB is much wider and taller compared to the SB. When programming voltage spikes are applied to the control gate (CG), i.e. p++-Si, carriers tunnel from the p++-Si into the Pt/TiN floating gate (FG) and remains trapped even after the release of the spike. These trapped charges on the FG screen the electric field from CG and thereby shifts the V_{TH}. The total amount of charge injected into the FG, and hence shift in V_{TH} of the MoS_2 FET can be controlled by the amplitude, duration, and polarity of $V_{P/D}$.*

Supplementary Information 8

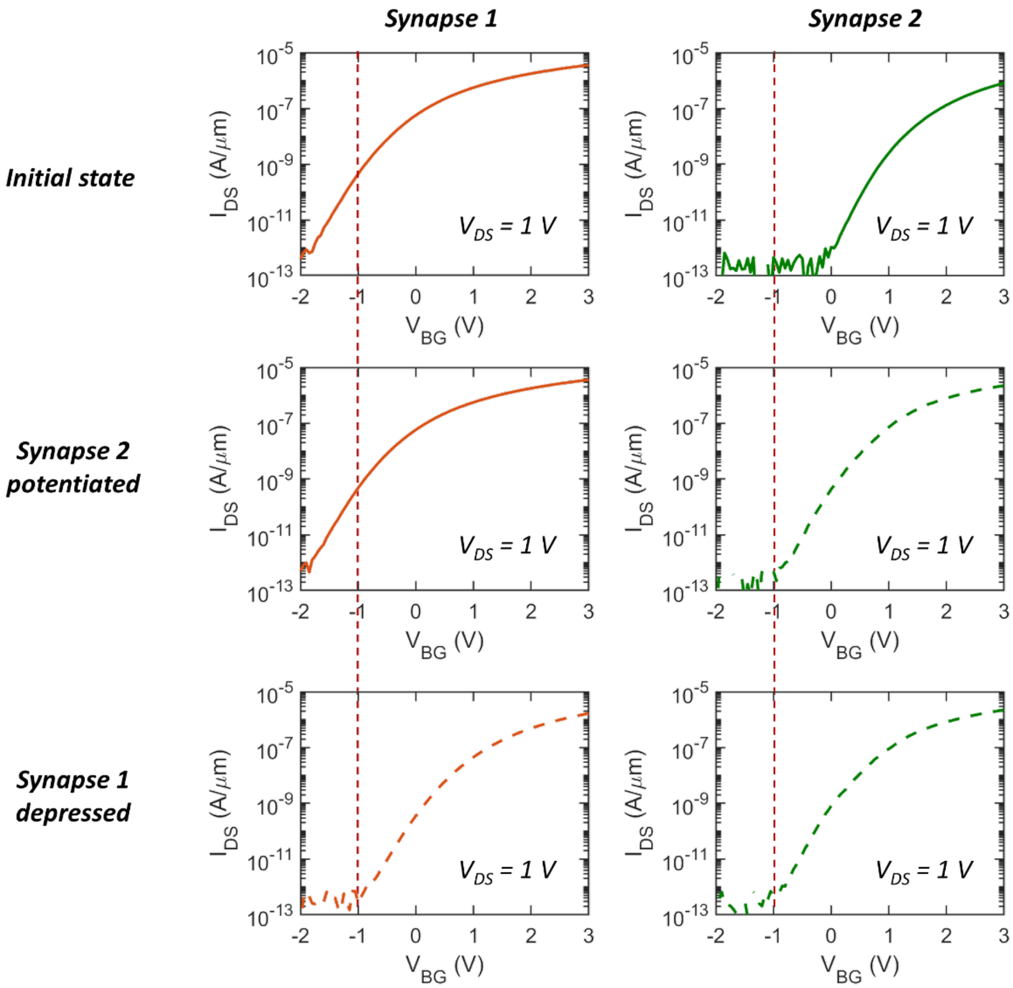

Figure S8: *Transfer characteristics of 2 adjacent MoS_2 synapses subjected to local potentiation and depression. When synapse 2 is potentiated, synapse 1 remains unaltered. Similarly, when synapse 1 is depressed synapse 2 retains its potentiated state. This proves that, despite of global back-gate, synapses can be potentiated or depressed locally.*

Supplementary Information 9

Table 1: Energy expenditure during the spike-count and spike-timing based unsupervised learning, forgetting, and relearning using MoS_2 synapses under various conditions of potentiation and depression.

	Spike-count based unsupervised Learning	Spike-timing based unsupervised Learning
Weak Potentiation Strong Depression	10.2 nJ	0.97 nJ
Strong Potentiation Weak Depression	9.6 nJ	0.97 nJ
Strong Potentiation Strong Depression	9.7 nJ	0.97 nJ