SCIENCE CHINA
Information Sciences

• **Supplementary File** •

Lead-free perovskites-based photonic synaptic devices with zero electric energy consumption

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Appendix A Supporting Figures

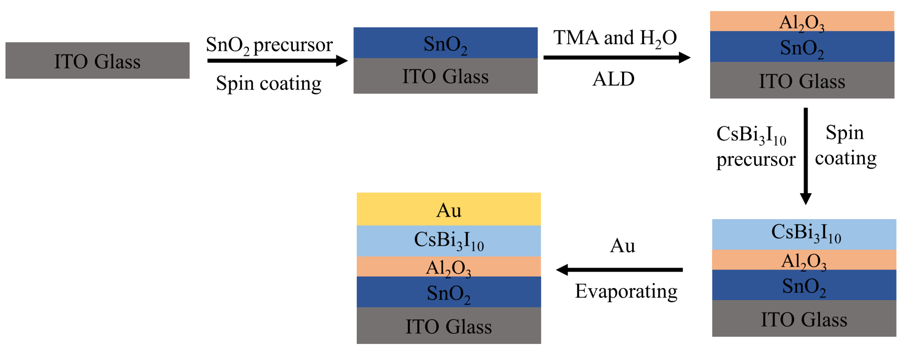

Figure S1 Schematic diagram of the device fabrication process.

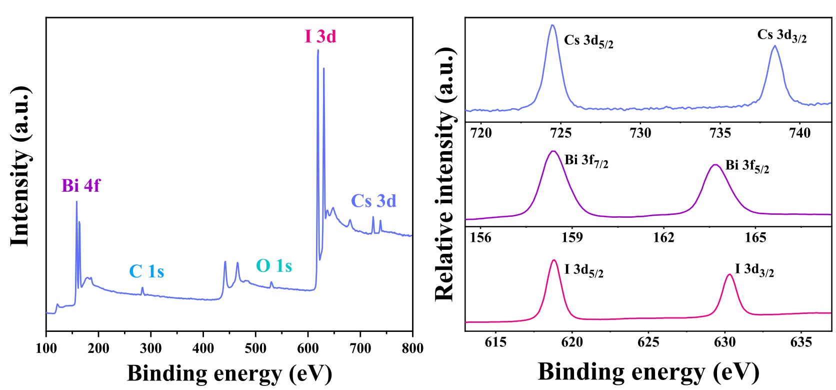

Figure S2 (a) Wide-range XPS scan of $CsBi_3I_{10}$ films deposited on SnO_2 layer with Al_2 O_3 of 0.5 nm. (b) XPS spectrum of the $CsBi_3I_{10}$.

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† Dandan HAO and Di YANG have the same contribution to this work.

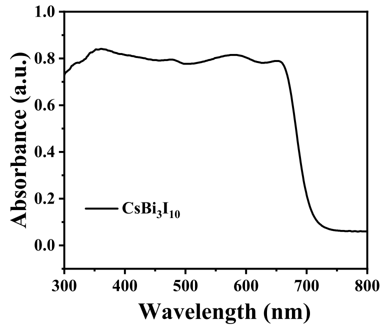

Figure S3 Absorption spectrum of $CsBi_3I_{10}$ film.

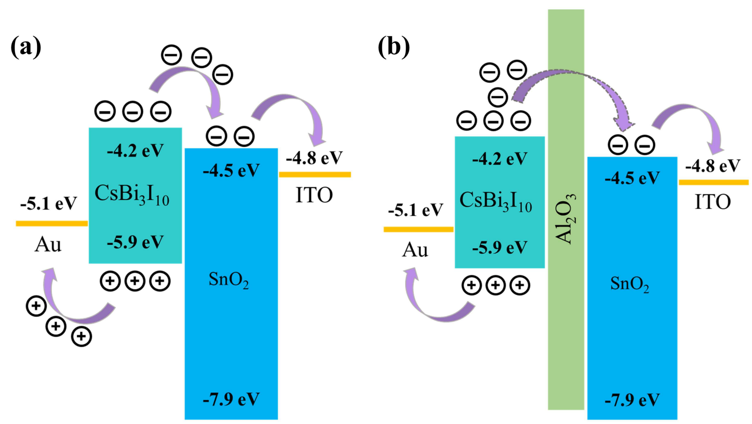

Figure S4 The band diagram of the (a) $ITO/SnO_2/Al_2O_3/CsBi_3I_{10}$/Au and (b) $ITO/SnO_2/Al_2O_3/CsBi_3I_{10}$/Au devices under light illumination.

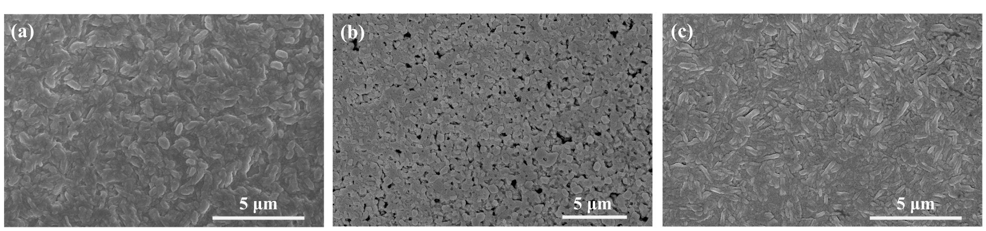

Figure S5 SEM images of $CsBi_3I_{10}$ with the thickness of Al2O3 of (a) 0 nm, (b) 0.5 nm, and (c) 1 nm.

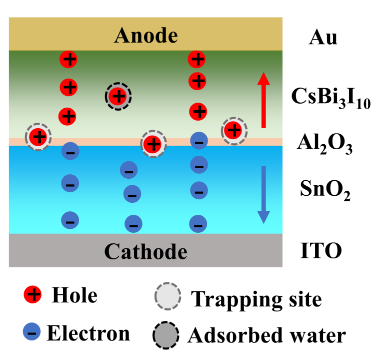

Figure S6 The working mechanism diagram of the $CsBi_3I_{10}$-SPPS.

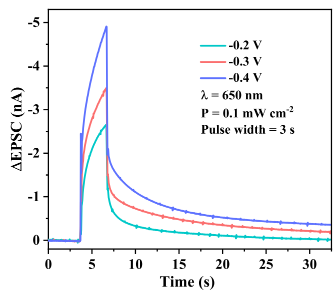

Figure S7 EPSC responses of the $CsBi_3I_{10}$-SPPS under a light stimulation (3 s, 0.1 mW cm^{-2}) at -0.2, -0.3, and -0.4 V.

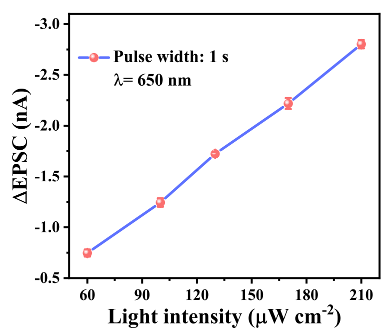

Figure S8 Dependence of ΔEPSC on the pulse intensity.

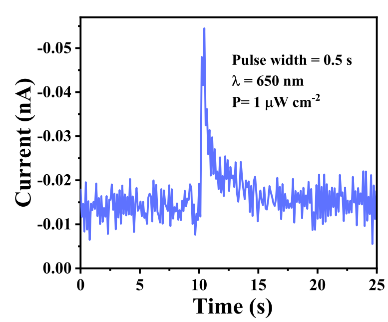

Figure S9 EPSC behavior triggered by a light pulse of 1 W cm^{-2}.

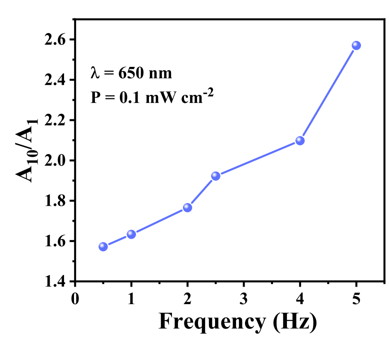

Figure S10 The EPSC gain (A_{10}/A_1) plotted with the increase of the light spike frequency.

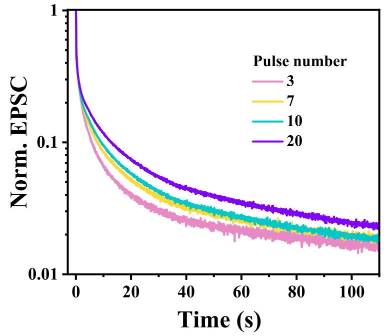

Figure S11 Decay processes of the device after the removal of light pulses with different pulse numbers.

Table S1 Energy consumption comparison of perovskites-based photonic synapses

Device structure	Lead or lead-free	Wavelength (nm)	Operation voltage (V)	Energy er spike (pJ)	Ref.
pentacene/PMMA$^{a)}$/$CsPbBr_3$ QDs	lead	365	0.2	1400	[1]
$CsPbBr_3$ QDs/PQT-12$^{b)}$	lead	500	−1	600	[2]
DPPDTT$^{c)}$/$CsPbBr_3$ QDs	lead	450	−0.2	0.0005	[3]
PVP$^{d)}$:$CsPbBr_3$ QDs/PDVT-10$^{e)}$	lead	400 to 500	−0.5	4.1	[4]
P3HT$^{f)}$/$CsPbBr_3$ QD nanofibril	lead	450	−0.001	0.00018	[5]
Si NW/$CH_3NH_3PbI_3$	lead	532	0.3	1	[6]
$CH_3NH_3PbBr_3$-RhB/pentacene	lead	450 to 650	-5×10^{-5}	0.00125	[7]
$CH_3NH_3PbBr_3$ QDs grown from graphene lattice	lead	440	0.5	36.75	[8]
$CH_3NH_3PbBr_3$-ZnO	lead	365 to 520	0.1	500	[9]
$FAPbBr_3$ NC/SWCNT	lead	405	0.5	0.0074	[10]
$CsPbBr_3$-QDs/MoS_2	lead	405	0.1	42930	[11]
PCBM$^{g)}$/$MAPbI_3$:Si NCs/Spiro-OMeTAD$^{h)}$	lead	375 to 808	0	0	[12]
P3HT/$FAPbBr_3$QDs	lead	450	−0.0005	3×10^{-5}	[13]
$CsBi_3I_{10}$/SWCNTs	lead-free	450	−1	1	[14]
PDPP4T$^{i)}$/$CsPbBr_3$ QDs	lead	450	-10^{-5}	0.0013	[15]
IGZO/$CsPbBr_3$ QDs/IGZO	lead	650	1	130	[16]
C8-BTBT$^{j)}$/PS$^{k)}$/$CsPbBr_3$ QDs	lead	400 to 500	−0.01	4.1	[17]
SnO_2/Al_2O_3/$CsBi_3I_{10}$	lead-free	650	0	0	Our work

[1] a) PMMA: Polymethyl methacrylate; b) PQT-2: Poly(3,3-didodecylquarterthiophene); c) DPPDTT: (poly[2,5-(2-octyldodecyl)-3,6-diketopyrrolopyrrole-alt-5,5-(2,5-di(thien-2-yl)thieno [3,2-b]thiophene)]; d) PVP: Polyvinylpyrrolidone; e) PDVT-10: poly[2,5-bis(2-decyltetradecyl)pyrrolo[3,4-c]pyrrole-1,4(2H,5H)-dione-alt-5,5-di(thiophen-2-yl)-2,2-(E)-2-(2-(thiophen-2-yl)vinyl)thiophene]; f) P3HT: poly(3-hexylthiophene); g) PCBM: Phenyl-C61-Butyric-Acid-Methyl-Ester; h) Spiro-OMeTAD: 2,2,7,7-Tetrakis(N,N-p-dimethoxyphenylamino)-9,9-spirobifluorene; i) PDPP4T: poly[2,5-bis(2-octyldodecyl)pyrrolo[3,4-c]-pyrrole-1,4(2H,5H)-dione-3,6-diyl)-alt-(2,2;5,2;5,2-quaterthiophen-5,5-diyl)]; j) C8-BTBT: 2,7-Dioctyl[1]benzothieno[3,2-b][1]benzothiophene; k) PS: poly(styrene).

References

1 Wang Y; Lv Z; Chen J, et al. Photonic Synapses Based on Inorganic Perovskite Quantum Dots for Neuromorphic Computing. Adv Mater, 2018, 30: 1802883.

2 Wang K; Dai S; Zhao Y, et al. Light-Stimulated Synaptic Transistors Fabricated by a Facile Solution Process Based on Inorganic Perovskite Quantum Dots and Organic Semiconductors. Small, 2019, e1900010.

3 Hao D; Zhang J; Dai S, et al. Perovskite/Organic Semiconductor-Based Photonic Synaptic Transistor for Artificial Visual System. ACS Appl Mater Interfaces, 2020, 12: 39487-39495.

4 He W; Fang Y; Yang H, et al. A Multi-Input Light-stimulated Synaptic Transistor for Complex Neuromorphic Computing. J Mater Chem C, 2019, 7: 12523-12531.

5 Ender Ercan Y-C L, Wei-Chen Yang, and Wen-Chang Chen. Self-Assembled Nanostructures of Quantum Dot/Conjugated Polymer Hybrids for Photonic Synaptic Transistors with Ultralow Energy Consumption and Zero-Gate Bias. Adv Funct Mater, 2022, 32: 2107925.

6 Yin L; Huang W; Xiao R, et al. Optically Stimulated Synaptic Devices Based on the Hybrid Structure of Silicon Nanomembrane and Perovskite. Nano Lett, 2020, 20: 3378-3387.

7 Wang X; Hao D; Huang J. Dye-sensitized perovskite/organic semiconductor ternary transistors for artificial synapses. Sci China Mater, 2022, 65: 2521-2528.

8 Pradhan B; Das S; Li J, et al. Ultrasensitive and ultrathin phototransistors and photonic synapses using perovskite quantum dots grown from graphene lattice. Sci Adv, 2020, 6: eaay5225.

9 Ge S; Huang F; He J, et al. Bidirectional Photoresponse in Perovskite-ZnO Heterostructure for Fully Optical-Controlled Artificial Synapse. Adv Opt Mater, 2022, 10: 2200409.

10 Hao J; Kim Y-H; Habisreutinger S N, et al. Low-energy room-temperature optical switching in mixed-dimensionality nanoscale perovskite heterojunctions. Sci Adv, 2021, 7: eabf1959.
11 Cheng Y; Li H; Liu B, et al. Vertical 0D-Perovskite/2D-MoS_2 van der Waals Heterojunction Phototransistor for Emulating Photoelectric-Synergistically Classical Pavlovian Conditioning and Neural Coding Dynamics. Small, 2020, 16: 2005217.
12 Huang W; Hang P; Wang Y, et al. Zero-power optoelectronic synaptic devices. Nano Energy, 2020, 73: 104790.
13 Chen J-Y; Yang D-L; Jhuang F-C, et al. Ultrafast Responsive and Low-Energy-Consumption Poly(3-hexylthiophene)/Perovskite Quantum Dots Composite Film-Based Photonic Synapse. Adv Funct Mater, 2021, 31: 2105911.
14 Liu Z; Dai S; Wang Y, et al. Photoresponsive Transistors Based on Lead-Free Perovskite and Carbon Nanotubes. Adv Funct Mater, 2019, 30: 1906335.
15 Chen T; Wang X; Hao D, et al. Photonic Synapses with Ultra-Low Energy Consumption Based on Vertical Organic Field-Effect Transistors. Adv Opt Mater, 2021, 9: 2002030.
16 Duan H; Liang L; Wu Z, et al. IGZO/$CsPbBr_3$-Nanoparticles/IGZO Neuromorphic Phototransistors and Their Optoelectronic Coupling Applications. ACS Appl Mater Interfaces, 2021, 13: 30165-30173.
17 Shi Q; Liu D; Hao D, et al. Printable, ultralow-power ternary synaptic transistors for multifunctional information processing system. Nano Energy, 2021, 87: 106197.