Supporting Information

A Multimodal Artificial Sensory Neuron Realized by Bio-Voltage-Level Threshold Switching Memristor

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Supporting Figures

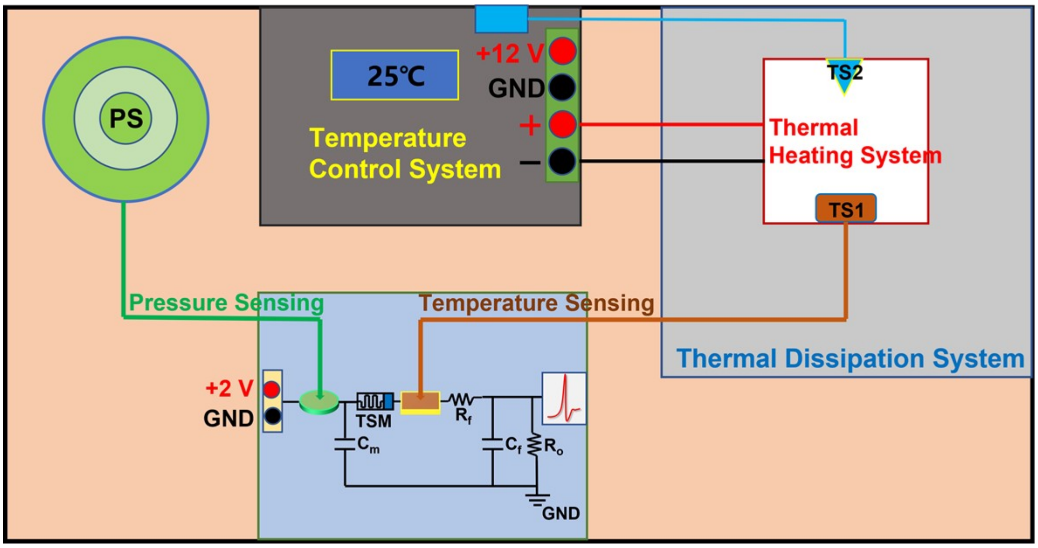

Fig. S1. A pressure-temperature multimodal control system responsible for gradient adjustment of pressure and temperature parameters on circuits.

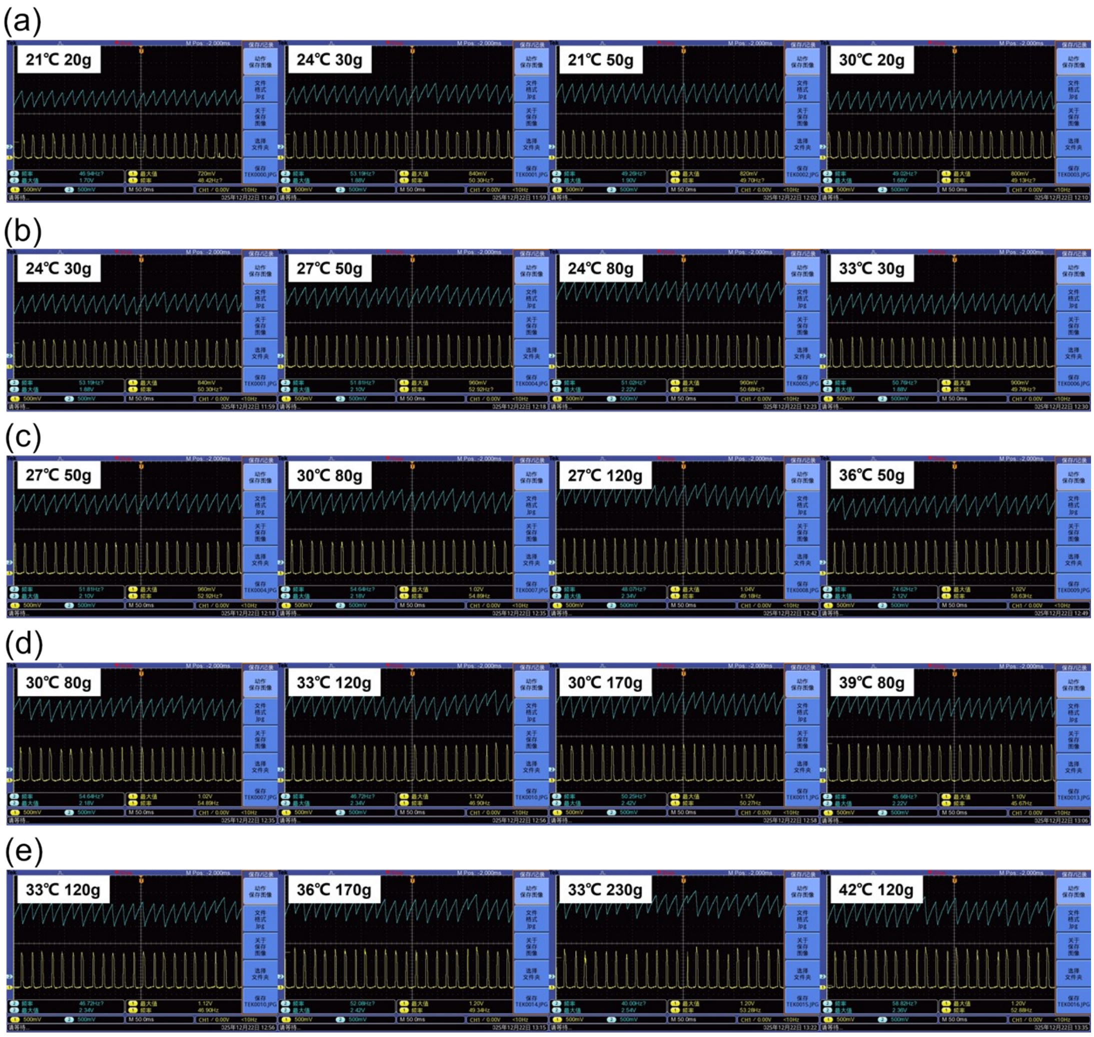

Fig. S2. (a) - (e) show the oscilloscope measurement results of the output spike voltage signals from the artificial neuron circuit in the five sets of comparative experiments, respectively.

Table S1. Performance Comparison of Al_2O_3/HfO_2-Based Devices with Different Structures.

Device Structure	V_{th}^+ (mV) [CV]	V_{th}^- (mV) [CV]	Electroforming voltage (V)	Endurance (cycles)
$Pt/Al_2O_3/HfO_2/Ag/Pt$[1]	1050±360 [34%]	-930±320 [34%]	-2	<100
$Pt/Al_2O_3/HfO_2/Ag$ NIs（50 nm）/Pt[1]	Unipolar	-20±1[6%]	No needing	<100
$Pt/Ag/Al_2O_3/HfO_2/Ag$ NIs（50 nm）/Pt	21.5±2.8 [13%]	-12.6±2.2 [18%]	No needing	>200

Table S2. Comparison of Minimum Start-up Power between $Pt/Ag/Al_2O_3/HfO_2/Ag$ NIs/Pt Devices and TSM Devices from Other Studies

Devices	**Threshold voltage**	**Threshold current**	**Start-up power**
Cu/a-Si/Pt[2]	0.50 V	0.7 μA	3.5×10^{-7} W
Ag/SnSe/Au[3]	0.47 V	0.4 μA	1.88×10^{-7} W
$Ag/Ti/HfSe_{2-x}O_y/Pt$[4]	0.54 V	2×10^{-5} μA	1.08×10^{-11} W
$TiN/NbO_X/TiN$[5]	1.25 V	20 μA	2.5×10^{-5} W
$Au/Ti/VO_2/Ti/Au$[6]	1.40 V	600 μA	8.4×10^{-4} W
$Pt/Ag/Al_2O_3/HfO_2/Ag$ NIs/Pt（Our work)	0.02 V	0.2 μA	4×10^{-9} W

Table S3. Technical Data and Physical Properties of the Pressure Sensors

Model number	IMS005-C40A
Thickness	0.3 mm
Shape	Flexible
Actuation force	20 g, Res. <= 500 kΩ
Sensitivity range	20 g to 2000 g
Resolution	Continuous
Non-actuated resistance	2 MΩ
Response time	5 ms
Operating temperature	-40℃~ +60℃

Lifetime	1million

Table S4. Technical Data and Physical Properties of the Temperature Sensors

Model number	MF52B
Resistance	10 kΩ at 25℃
Resistance Tolerance	±1%
B Value	3950 K at 25/50℃
B Value Tolerance	±1%
Sensitivity range	-40℃~ +125℃

Table S5. The Parameters for the Single-modal Pressure Test (fixed values: V_{cc}=3 V; R_c=82 kΩ; C_m=220 nF; T_{charge}=15 ms; R_{LRS}=11.6 kΩ; R_{temp_fixed}=10.5 kΩ; R_o=20 kΩ).

	V_{c0} (V)	R_{press} (kΩ)
20g	1.3	180
30g	1.36	152
50g	1.4	115
80g	1.48	82
120g	1.56	60
170g	1.62	46
230g	1.68	35
300g	1.74	30
380g	1.82	24
470g	1.9	20

Table S6. The Parameters for the Single-modal Temperature Test (fixed values: V_{cc}=3 V; R_c=82 kΩ; C_m =220 nF; T_{charge}=15 ms; R_{LRS}=11.6 kΩ; R_{press_fixed}=60 kΩ; R_o=20 kΩ).

	V_{c0} (V)	R_{temp} (kΩ)
21℃	1.58	12.2
24℃	1.6	10.5
27℃	1.6	9.2
30℃	1.62	8.4
33℃	1.64	7.5
36℃	1.62	6.6
39℃	1.62	6
42℃	1.62	5.2
45℃	1.64	4.7
48℃	1.66	4.2

Note: V_{c0} is the initial voltage value of C_m randomly selected from 100 actual measured spike firings.

Table S7. Experimental Condition Settings for Different Groups

Group	Base	Multimodal	High-Pressure	High-Temperature
1	21℃ 20 g	24℃ 30 g	21℃ 50 g	30℃ 20 g
2	24℃ 30 g	27℃ 50 g	24℃ 80 g	33℃ 30 g
3	27℃ 50 g	30℃ 80 g	27℃ 120 g	36℃ 50 g

4	30℃ 80 g	33℃ 120 g	30℃ 170 g	39℃ 80 g
5	33℃ 120 g	36℃ 170 g	33℃ 230 g	42℃ 120 g

References

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