**Supplementary Information**

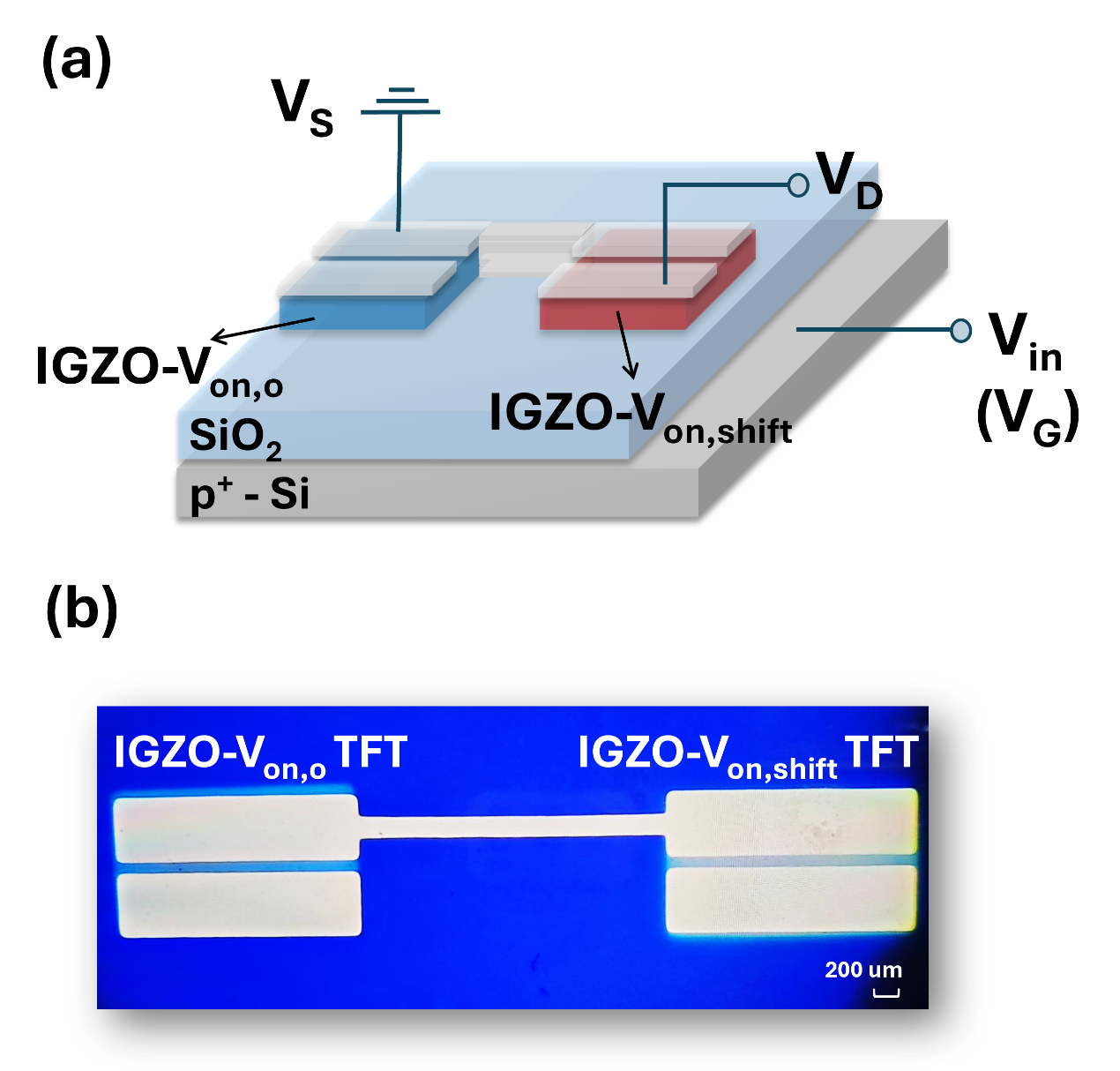
***IGZO Phototransistor-Based Ternary Inverter Integrating Optical Sensing and Weight Quantization in Ternary Neural Networks for Color Image Recognition***

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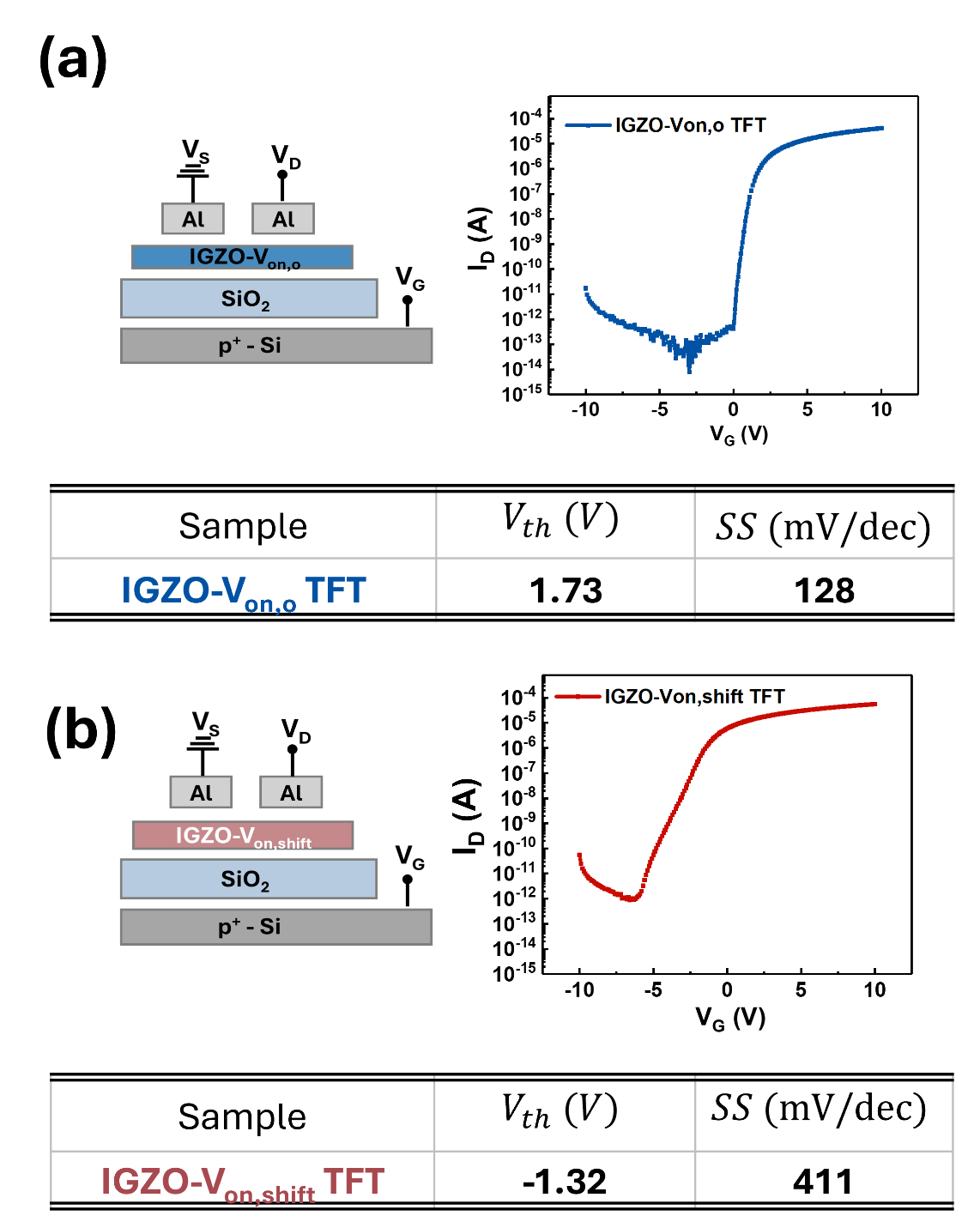
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**Figure S1.** (a) Schematic of the IGZO parallel TFPTs device and (b) Optical microscope (OM) image of the actual device.



**Figure S2.** Transfer characteristics (ID-VG) of IGZO thin-film phototransistors fabricated under different sputtering powers (30 W, 50 W, 70 W, and 100 W), measured at a drain voltage of VD = 1 V.



**Figure S3.** Device structures and transfer characteristics (ID–VG) of two IGZO TFPTs with distinct threshold voltages. (a) The IGZO-Von,o TFPT exhibits a positive threshold voltage (Vth), corresponding to enhancement-mode behavior. (b) The IGZO-Von,shift TFPT shows a negative Vth, indicative of depletion-mode operation. The subthreshold swing (S.S.) is also degraded in the latter, suggesting increased defect density1, 2. These differences enable complementary functions in ternary logic circuits.

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**Figure S4.** UV-Vis transmittance (T%) and absorbance (Abs.) spectra of (a) IGZO-Von,o and (b) IGZO-Von,shift. Tauc plot method of the (c) IGZO-Von,o thin film for optical band gap (Eg) estimation (~3.6 eV) and (d) IGZO-Von,shift thin film for optical band gap (Eg) estimation (~3.7 eV).

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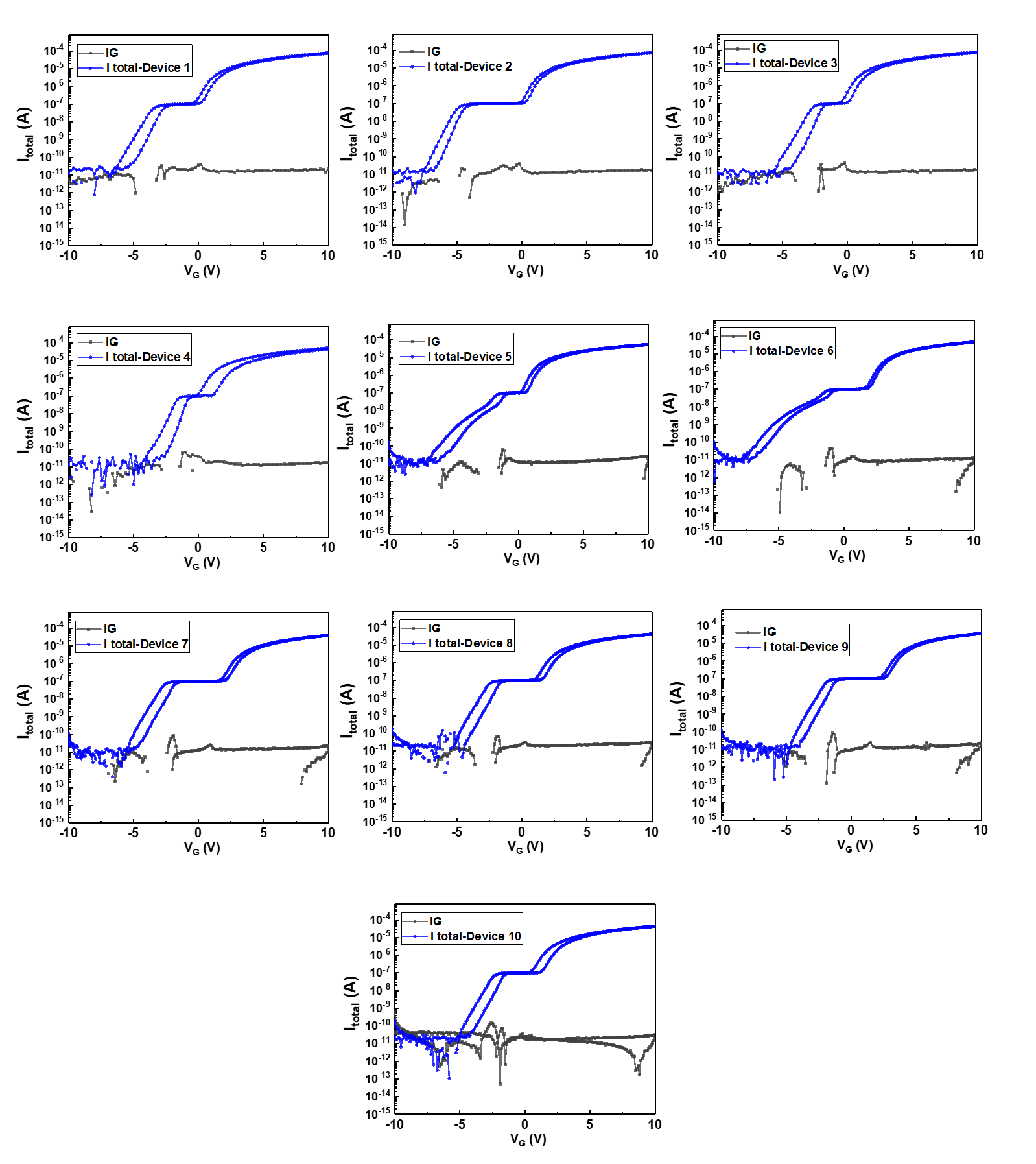
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**Figure S5.** UPS spectra of IGZO films with (a) IGZO-Von,o and (b) IGZO-Von,shift. The secondary electron cut-off (left) and valence band maximum (VBM, right) regions are shown to evaluate the electronic structure.

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**Figure S6.** The IGZO parallel TFPTs cycle-to-cycle variation in transfer characteristics curve (ID-VG) under VD=1 V. The grey curve represents leak current (IG).



**Figure S7.** The IGZO parallel TFPTs device-to-device variation in transfer characteristics curve (ID-VG) under VD=1 V. The grey curve represents leak current (IG).



**Figure S8.** Cycle-to-cycle variation of the transfer characteristics (ID-VG) of the parallel IGZO TFPTs measured under illumination at VD = 1 V. The grey curves indicate the leak current (IG).

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**Figure S9.** Transfer characteristics (ID-VG) of the parallel IGZO TFPTs under repeated optical exposure. The curves are measured in the dark and after continuous 405nm laser illumination at 10mW/cm2 for 1, 3, 5, and 10 min.

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**Figure S10.** Bias stress measurement of the parallel IGZO TFPTs. The transfer characteristics (ID-VG) were measured before stress and after applying a positive gate bias stress (VG = 10 V) for 10 sec and 60 sec.

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**Figure S11.** (a) Schematic diagram of the IGZO-based binary inverter composed of an IGZO–Von,o TFPT and a load resistor, with Vin​ controlling the output voltage (Vout)​. **(b)** Voltage transfer characteristics (VTC) of the inverter under various drain voltages (VD​=1~5 V), showing logic 0/1 switching behavior and **(c)** Corresponding voltage gain (dVout​/dVin​) of the inverter. **(d)** Retention behavior of the binary inverter, indicating that the logic ‘0’ state is not stable due to the absence of an effective pull-down path to discharge the output node, leading to instability at Vout=0.5 V.

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**Figure S12.** (a) A ternary inverter composed of two IGZO TFPTs with distinct turn-on voltages connected in parallel, followed by two series load resistors. The voltage transfer curve exhibits three distinct output states corresponding to different input regimes: (i) At large negative Vin ​, both TFPTs are off, presenting high impedance and effectively blocking current flow; the output node is pulled up to VDD ​, representing logic state ‘1’. (ii) As Vin increases to activate only the IGZO–Von,shift TFPT, both load resistors conduct and share the voltage drop equally, resulting in a stable Vout of 0.5 V, corresponding to logic state ‘0’. (iii) Further increase of Vin turns on the IGZO–Von,o TFPT, causing the output node to discharge through the first resistor, yielding Vout=0 V, which corresponds to logic state ‘–1’. (b) The VTC curve of the ternary inverter under increasing drain voltage VDD from 1 V to 5 V reveals two pronounced transitions. (c) The first derivative plot (dVout/dVin​) highlights two distinct peaks3, corresponding to sharp output drops at two critical input voltages. The first transition point (Vsensor​) marks the voltage at which Vout rapidly drops to 0.5 V, entering the logic ‘0’ state. The second transition corresponds to the subsequent drop from logic ‘0’ to logic ‘–1’, indicating the full activation of two TFPTs.

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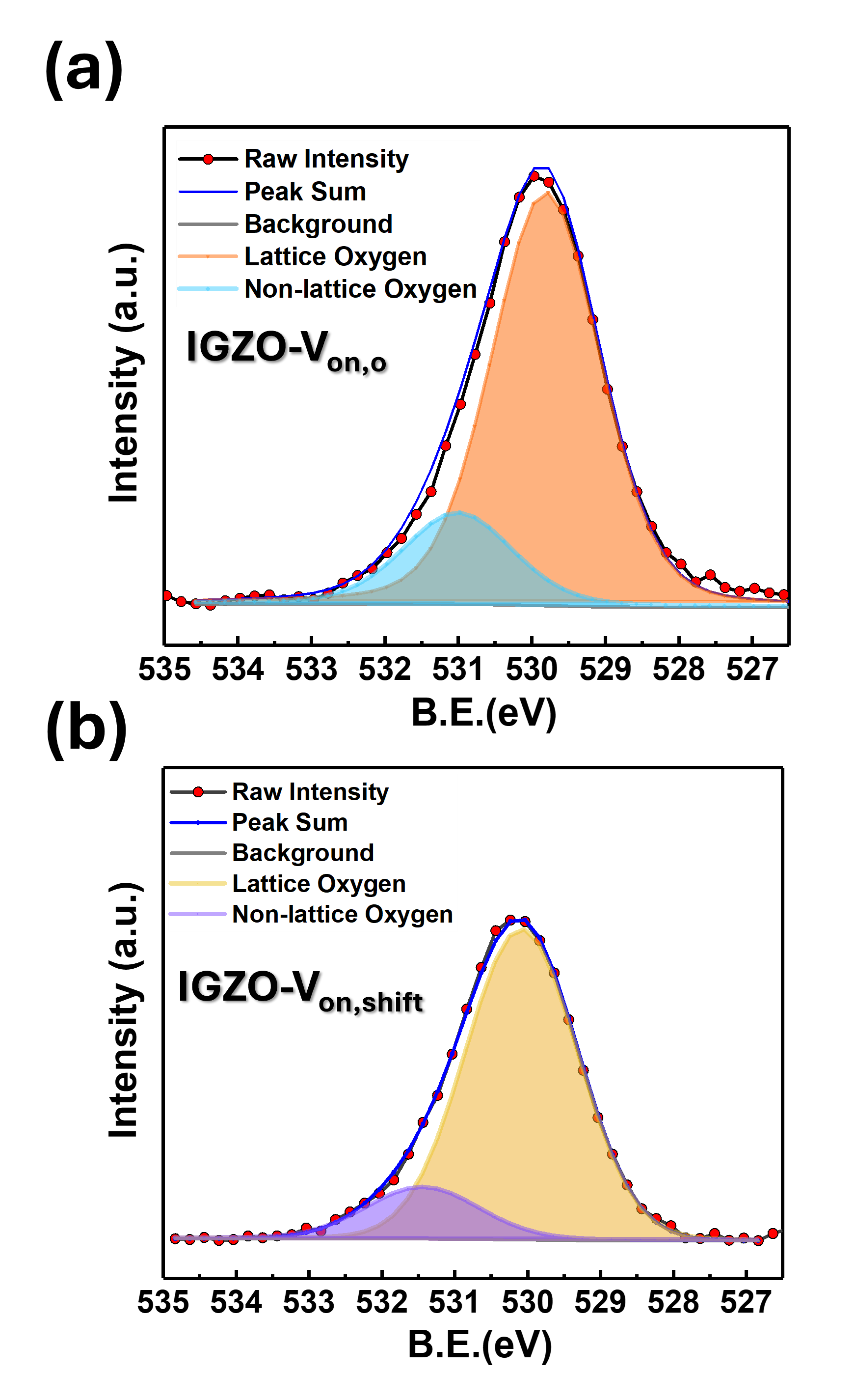
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**Figure S13.** Transfer characteristics (ID–VG) of IGZO-Von,o TFPT under different light power densities and wavelengths. Each plot compares the pristine (dark) state with illuminated conditions at increasing power densities (1–20 mW/cm²) using (a) red (670 nm), (b) green (520 nm), and (c) blue (405 nm) laser sources, respectively. Illumination causes a negative shift in turn-on voltage and an increase in drain current, with blue light inducing the most pronounced shift.

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**Figure S14.** Transfer characteristics (ID–VG) of the IGZO-Von,shift TFPT under varying light power densities and wavelengths. Each plot compares the pristine (dark) state with illuminated conditions at increasing power densities (1–20 mW/cm²) using (a) red (670 nm), (b) green (520 nm), and (c) blue (405 nm) laser sources, respectively. Illumination with all three wavelengths results in a pronounced negative shift in turn-on voltage and an increase in drain current.



**Figure S15.** (a) O 1s XPS spectrum of the IGZO-Von,o film, showing two deconvoluted peaks attributed to lattice oxygen (530.1 eV) and non-lattice oxygen (531.6 eV). (b) O 1s XPS spectrum of the IGZO-Von,shift film, showing an increased proportion of non-lattice oxygen.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Platform** | **Circuit complexity** | **Area** | **Scalability to large arrays** | **Ref.** |
| **This work** | Optical sensing and ternary weight quantization are intrinsically integrated at the same device without additional circuits. | The area is mainly defined by the parallel TFPT structures, avoiding extra peripheral circuitry. | Scalable to large pixel arrays through regular array layouts and voltage-based mapping schemes. |  |
| **memristive crossbars** | Although the device structure is simple, system operation requires additional peripheral circuits for optical sensing. | High cell density is achievable, but overall system area increases due to selectors and peripheral circuitry. | Scalable in principle, but light-to-voltage sensing peripheral circuits may not be compatible with large arrays. | [4] |
| **multi threshold CMOS circuits** | Intermediate logic states require multiple threshold devices and extra sensing circuits, increasing circuit complexity. | While core circuits are compact, additional sensing devices and write circuitry increase the total system area. | Compatible with standard CMOS processes, but large area sensing array integration increases system complexity. | [5] |
| **other oxide based ternary inverters** | Ternary behavior typically relies on oxide heterojunction devices within a limited bias window, sensing input and readout generally requires additional circuitry. | Ternary logic core can be compact, but adding sensing peripherals increases overall footprint. | Potentially scalable but maintaining a consistent ternary bias window and distributing bias signals across large arrays increasing system complexity. | [6] |

**Table S1.** Comparative summary of the proposed IGZO-based ternary optoelectronic approach and representative multi-level device platforms, including memristive crossbars, multi-threshold CMOS circuits, and other oxide-based ternary inverters.

**Table S2.** Off current, On current, 1st transient on/off ratio, 2nd transient on/off ratio and the VG range of the intermediate current state for 16 cycles.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Off current (A)** | **On current**  **(A)** | | **1st transient on/off ratio** | **2nd transient on/off ratio** | **Vintermediate (V)** |
| **Cycle 1** | 9.86 | | 7.93 | 9.42 | 8.54 | 2.7 |
| **Cycle 2** | 8 | | 7.3 | 1 | 7 | 2.7 |
| **Cycle 3** | 3 | | 7.1 | 2 | 7 | 2.7 |
| **Cycle 4** | 2 | | 7.1 | 3 | 7 | 3 |
| **Cycle 5** | 1 | | 7.0 |  | 7 | 3 |
| **Cycle 6** | 2 | | 7.4 |  | 7 | 3.1 |
| **Cycle 7** | 5 | | 7.4 |  | 7 | 3 |
| **Cycle 8** | 1 | | 7.4 |  | 7 | 3 |
| **Cycle 9** | 7 | | 7.3 | 1 | 8.42 | 2.7 |
| **Cycle 10** | 8 | | 7.4 | 1 | 7 | 3.3 |
| **Cycle 11** | 1 | | 7.2 | 8 | 7 | 3.5 |
| **Cycle 12** | 1 | | 7.4 |  | 7 | 3.4 |
| **Cycle 13** | 6 | | 6 | 1 | 6 | 4 |
| **Cycle 14** | 1 | | 7.4 | 8 | 7 | 3.6 |
| **Cycle 15** | 4 | | 6 | 2 | 6 | 4.1 |
| **Cycle 16** | 2 | | 7.2 | 3 | 7 | 4.6 |
| **Mean** |  | | 7.29 | 7.81 | 7 | 3.28 |
| **STD.** |  | |  | 2.05 | 4.39 | 0.547 |

**Table S3.** Off current, On current, 1st transient on/off ratio, 2nd transient on/off ratio and the VG range of the intermediate current state for 10 individual devices.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Off current (A)** | **On current**  **(A)** | **1st transient on/off ratio** | **2nd transient on/off ratio** | **Vintermediate (V)** |
| **Device 1** | 1.09 | 7.04 | 8.89 | 7.27 | 2.8 |
| **Device 2** | 1.55 | 6.90 | 6.28 | 7.09 | 4.2 |
| **Device 3** | 1.35 | 7.74 | 6.88 | 8.33 | 2.6 |
| **Device 4** | 1.19 | 4.92 | 7.64 | 5.39 | 2.3 |
| **Device 5** | 1.49 | 5.29 | 6.30 | 5.24 | 2.4 |
| **Device 6** | 1.19 | 4.50 | 6.45 | 5.86 | 2.8 |
| **Device 7** | 5.33 | 3.73 | 1.75 | 4.00 | 4.1 |
| **Device 8** | 2 | 4.01 | 4.65 | 4.32 | 3.5 |
| **Device 9** | 1.05 | 3.45 | 8.83 | 3.72 | 3.9 |
| **Device 10** | 2.47 | 4.14 | 3.85 | 4.35 | 3.1 |
| **Mean** |  | 5.17 | 5.00 | 5.56 | 3.17 |
| **STD.** |  | 1.45 | 3.03 | 1.48 | 0.672 |

**Table S4.** Summary statistics of Vsensor extracted from Figure 4h–j, including the mean (μ) and standard deviation (σ) under each RGB illumination condition.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | 0 mW/cm2 | 1 mW/cm2 | 5 mW/cm2 | 10 mW/cm2 | 15 mW/cm2 | 20 mW/cm2 |
| Red |  |  |  |  |  |  |
| mean (μ) | -4.05 | -5.2 | -6.16 | -7.67 | -9.12 | -10.25 |
| standard deviation (σ) | 0.67915 | 0.69372 | 0.75117 | 0.64479 | 0.71641 | 0.92669 |
| variance (σ2) | 0.46124 | 0.48125 | 0.56426 | 0.41575 | 0.51325 | 0.85875 |
| Green |  |  |  |  |  |  |
| mean (μ) | -4.05 | -11.23 | -12.9 | -15.47 | -17.57 | -21.24 |
| standard deviation (σ) | 0.67915 | 0.57619 | 1.34117 | 1.41713 | 1.71413 | 1.67571 |
| variance (σ2) | 0.46124 | 0.33199 | 1.79874 | 2.00826 | 2.93824 | 2.80800 |
| Blue |  |  |  |  |  |  |
| mean (μ) | -4.05 | -24.17 | -26.21 | -30.72 | -33.46 | -35.89 |
| standard deviation (σ) | 0.67915 | 1.23167 | 1.83044 | 1.81886 | 1.37541 | 1.32872 |
| variance (σ2) | 0.46124 | 1.51701 | 3.35051 | 3.30825 | 1.89175 | 1.76550 |

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Device structure** | **Functionality in NN** | **Operating Voltage (V)** | | **Endurance** **test** | **Pulse width for endurance** | **Optical Sensing** | **Application** | **Ref.** |
| **VDD** | **Vin (VG)** |
| **Al/IGZO/SiO2/p+Si** | Weight quantization | **1** | **(-10, 10)** | **500 cycles** | **100 ms** | **🗸** | **Color image recognition** | **This work** |
| **Au/Pd/Ti/s-CNT network/SiO2/Si** | Weight quantization | (2, 4) | (0, 4) | 🗴 | 🗴 | 🗴 | Digit recognition | [7] |
| **Ag/AgCl/Au/Ti/ ambipolar OSC/p-type OSC/SiO2/Si** | Weight quantization | 0.6 | (0, 0.9) | 50 cycles | 3 s | 🗴 | Digit recognition | [8] |
| **Ti/Pt/IGZO/IZO/IGZO/Al2O3/sapphire** | Weight quantization, Activation function | 1 | (-15, 15) | 🗴 | 🗴 | 🗴 | Digit recognition | [9] |
| **Au/MoTe2/MoS2/SiO2/Si** | Weight quantization | -3 | (-15, 30) | 🗴 | 🗴 | 🗴 | Digit recognition | [10] |

**Table S5.** Comparative Study of Transistors for Ternary Logic Circuit Applied in Quantized Neural Networks.

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